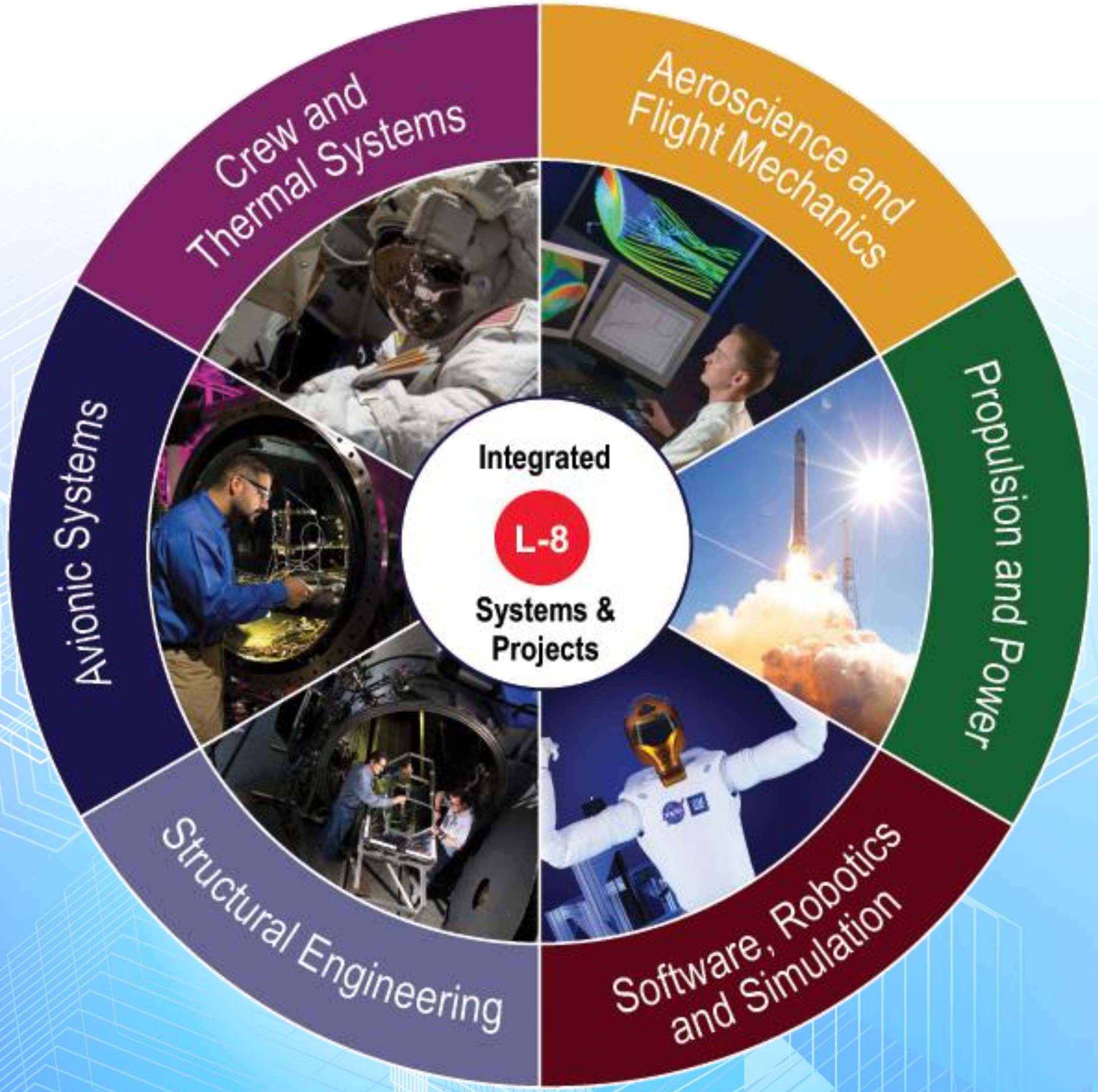
Johnson Space Center Engineering Directorate

L-8: Autonomy & Optimization

Gerald Condon

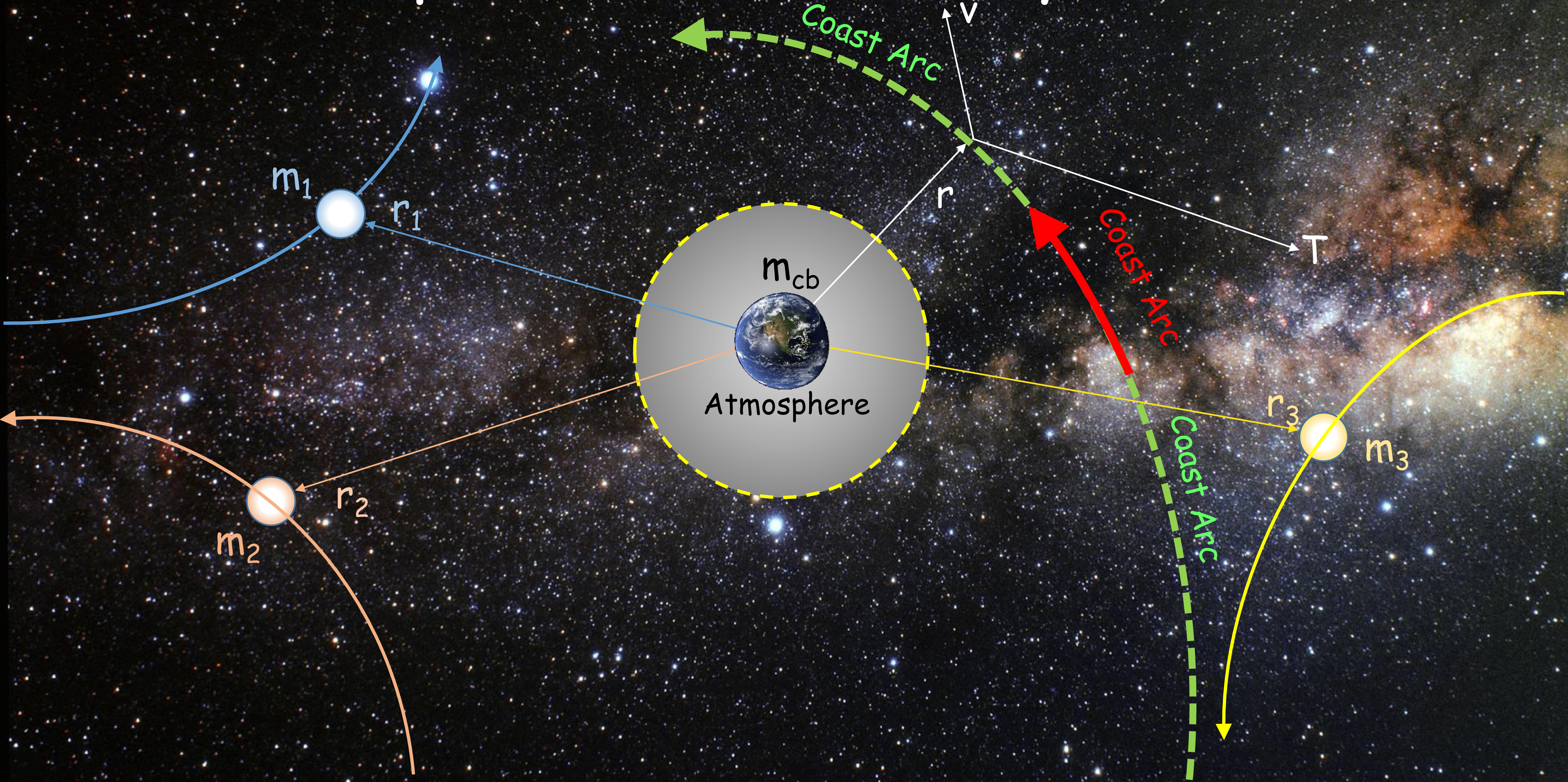
November 2016

JSC Engineering: HSF Exploration Systems Development



- We are sharpening our focus on Human Space Flight (HSF) Exploration Beyond Low Earth Orbit
- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
  - Various Roadmaps define the needed technologies
  - We are attempting to define our activities and dependencies
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025
  - Develop and Mature the technologies and systems needed
  - Develop and Mature the personnel needed
- We need collaborators to make it happen, and we think they can benefit by working with us.

Complex and Chaotic Dynamics



Example 1: Chaotic Motion in the Earth-Moon System

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caotic-motion-ex01-01.mp4

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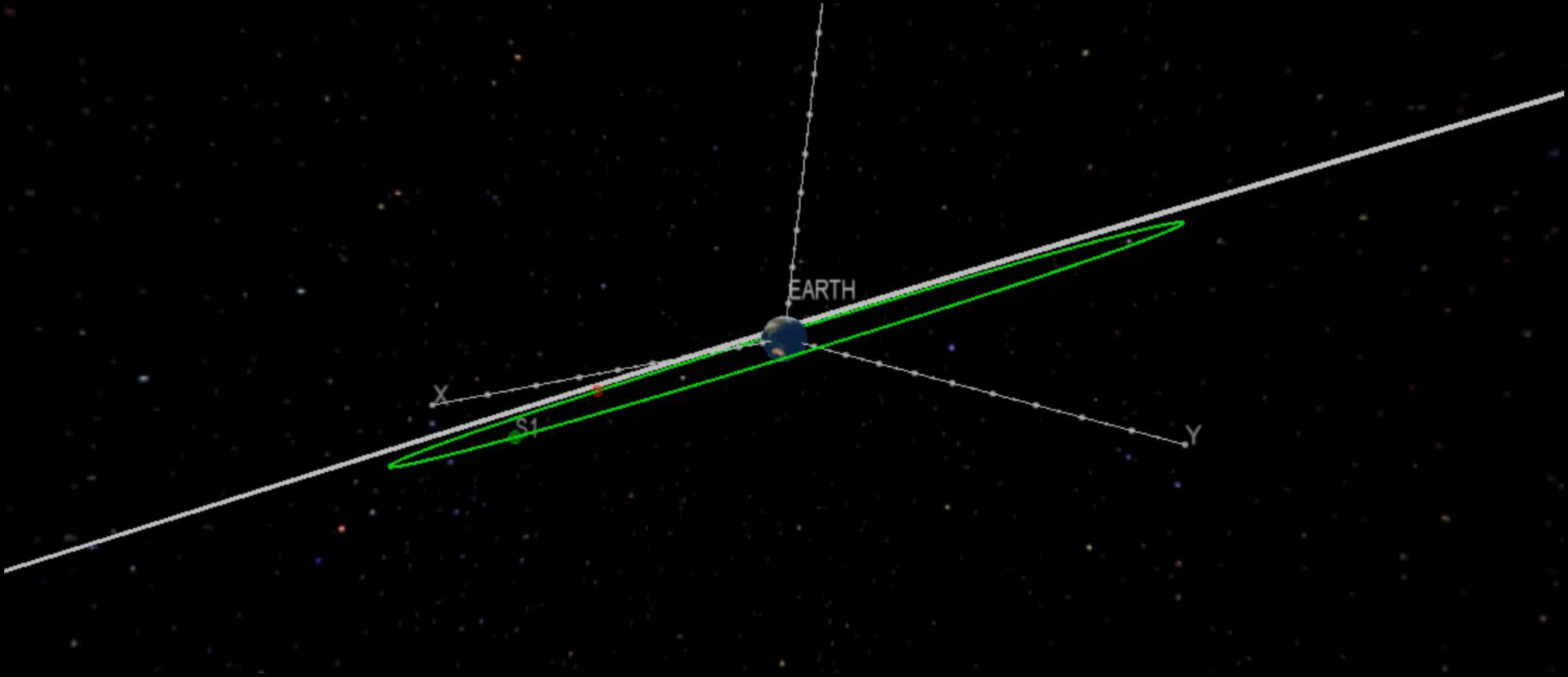

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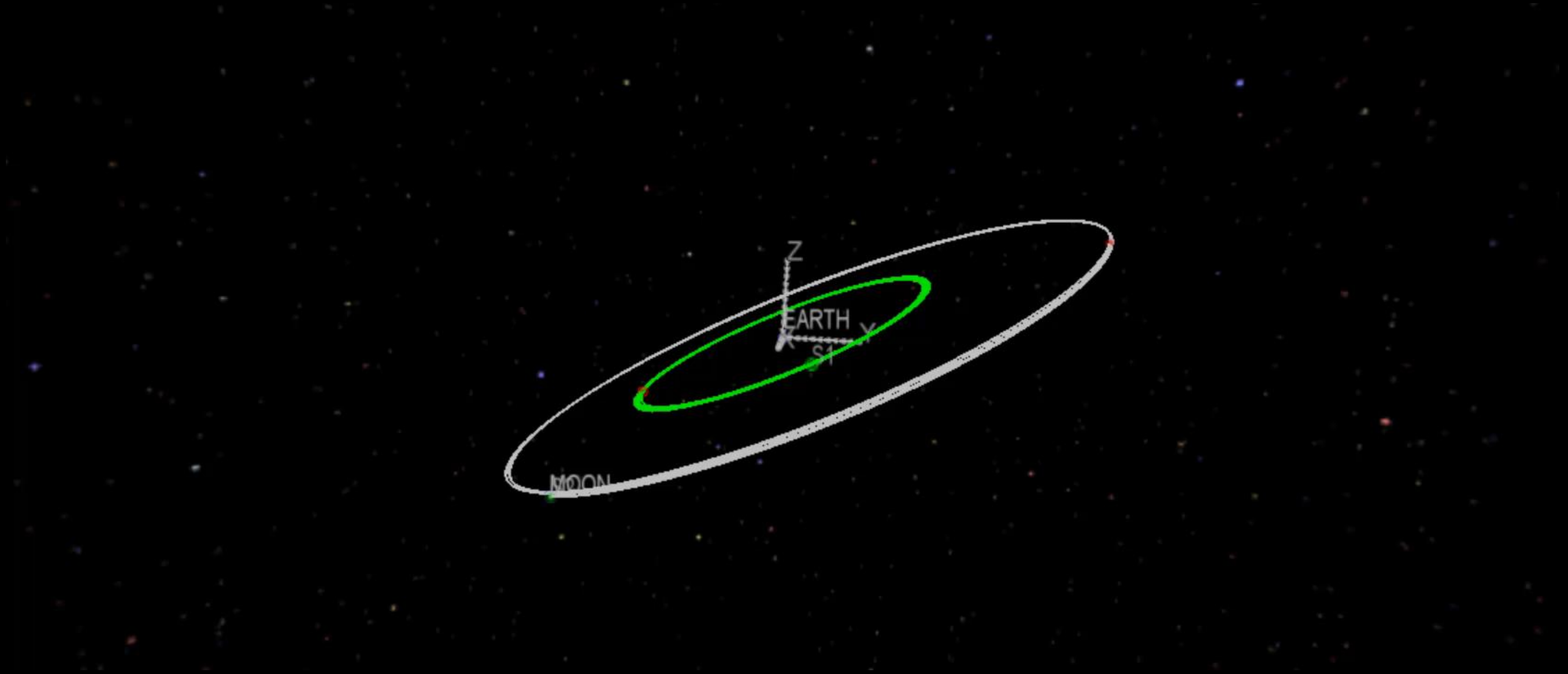

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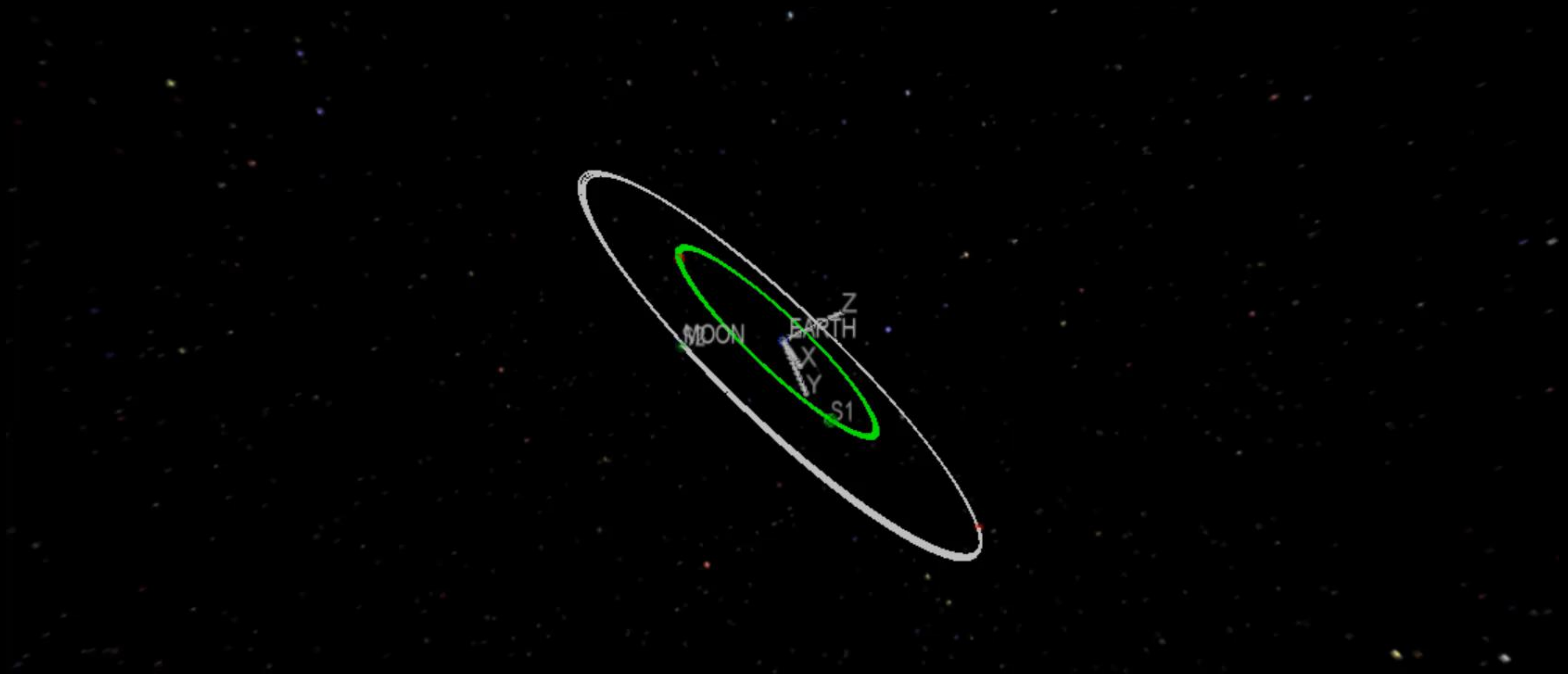

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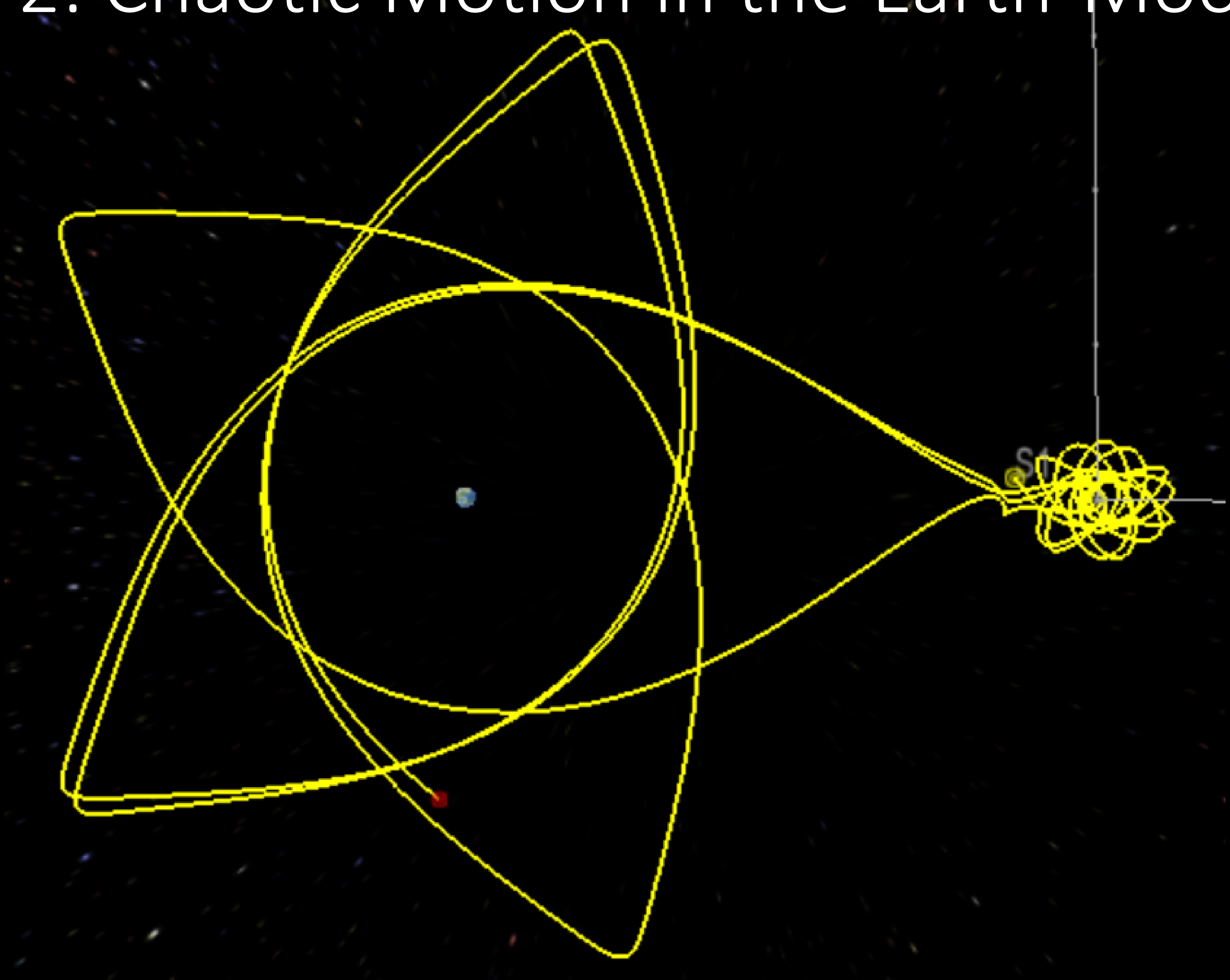
Example 2: Chaotic Motion in the Earth-Moon System



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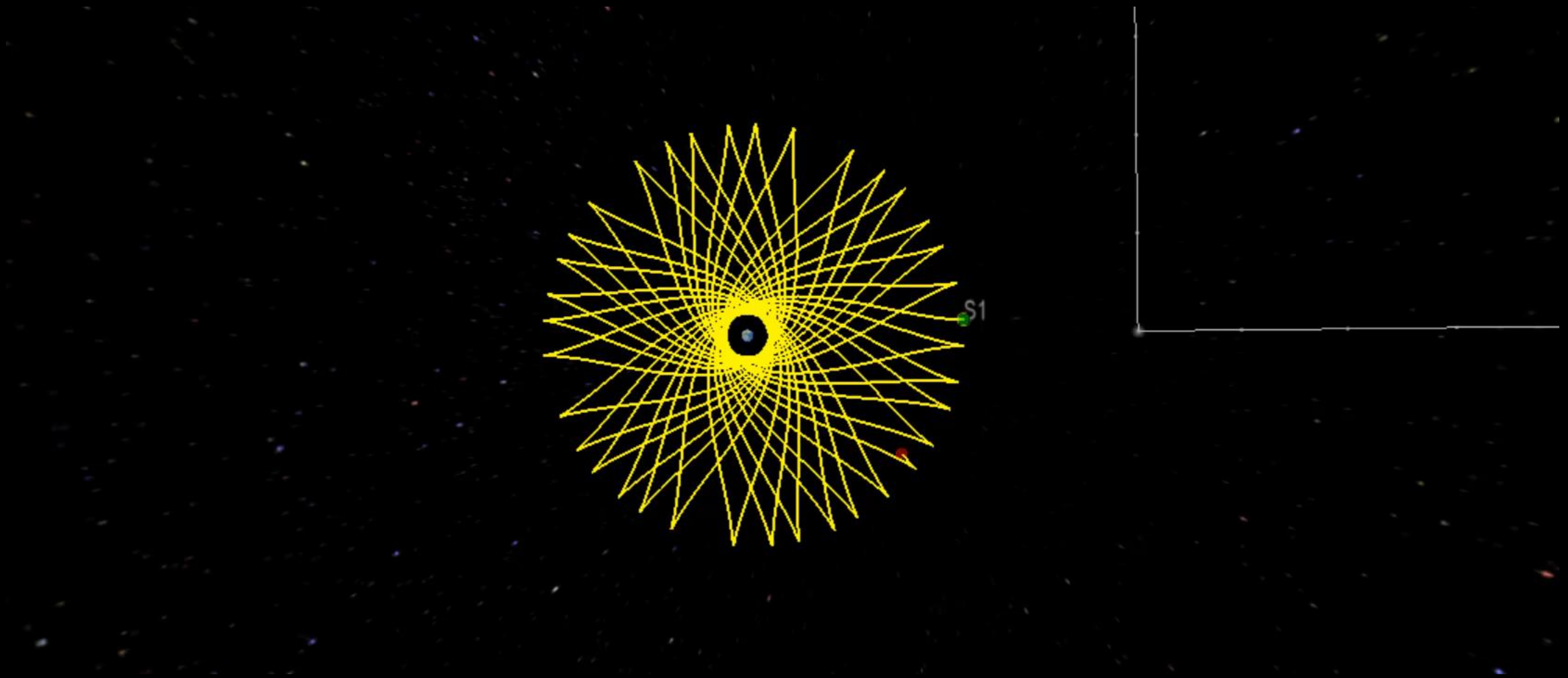

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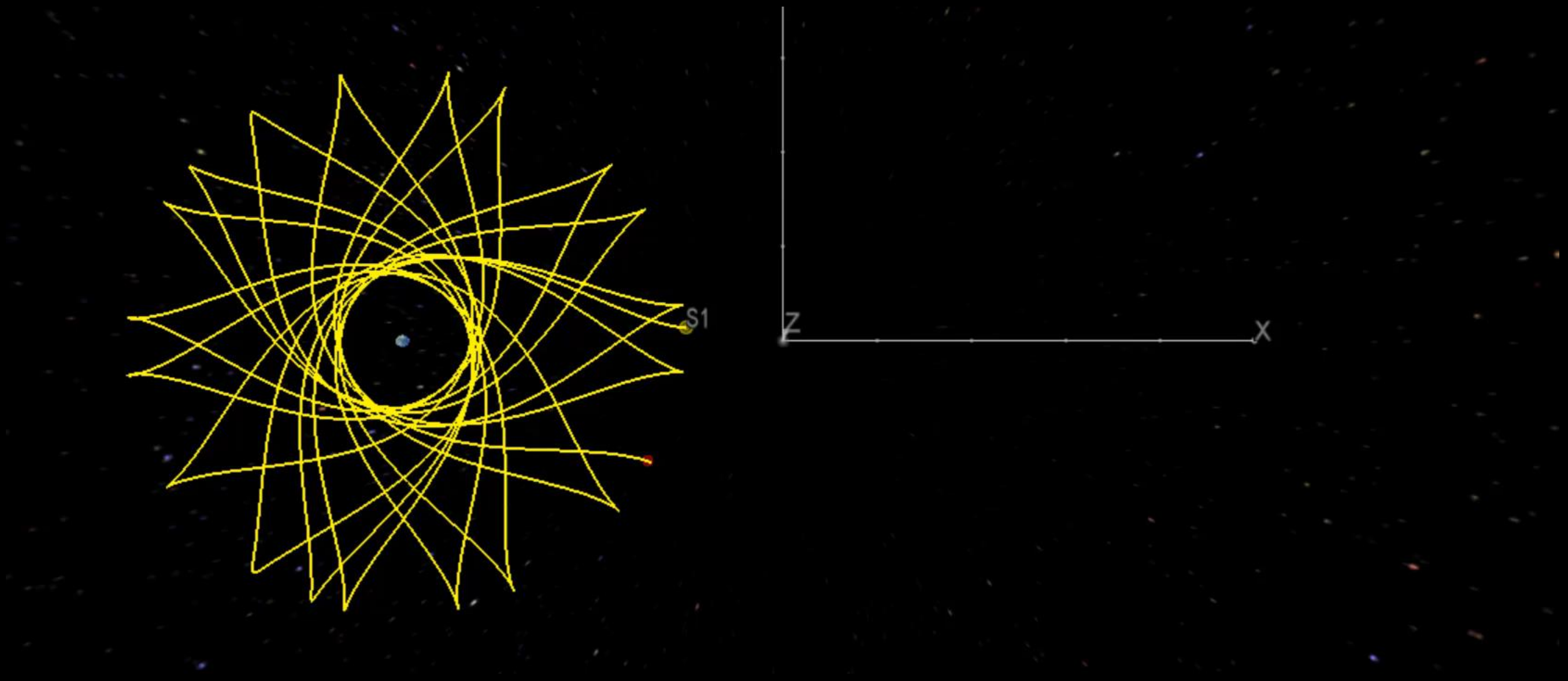

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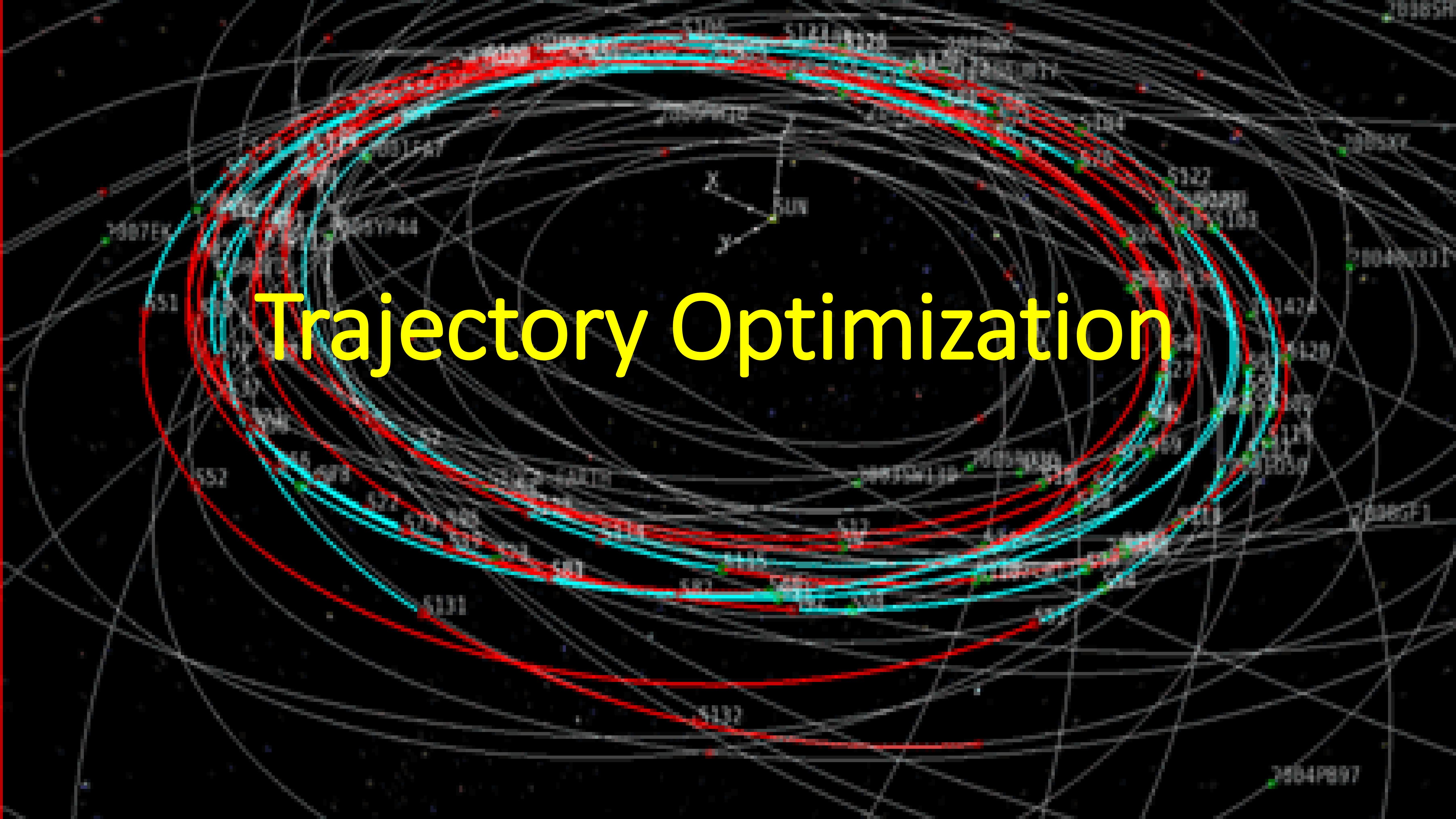
Trajectory Optimization



Basic Problem of Trajectory Optimization

Find the optimal value of a set of optimization variables, $\boldsymbol{X_p}$

- Initial conditions, times of maneuvers, directions of delta-v's, or steering direction of finite thrust vector, etc.

... subject to equality constraints, $\boldsymbol{C_{eq}(X_p) = 0}$

- Final position and velocity must match target, segments must be connected to be continuous, etc.

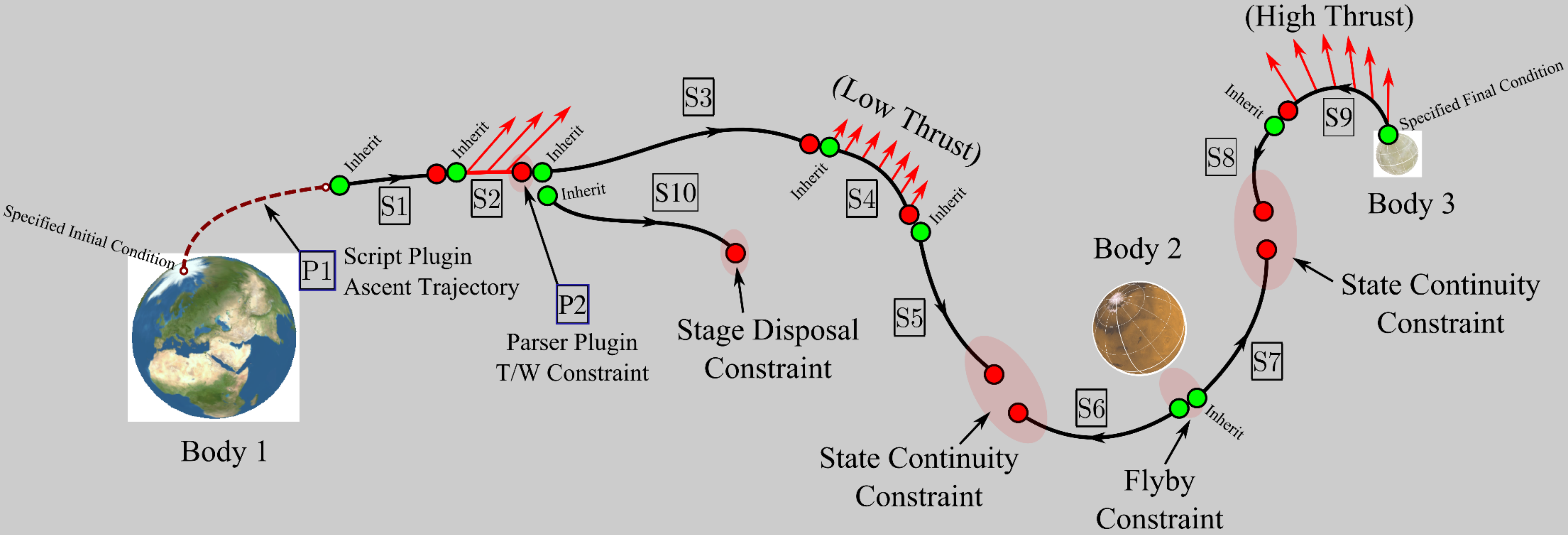
... and inequality constraints, $\boldsymbol{C_{ineq}(X_p) <= 0}$

- Minimum flyby radii, maximum allowable propellant, etc.

... while minimizing or maximizing and objective function, $\boldsymbol{F(X_p)}$

- Such as min delta-v, min-time, max impact velocity, etc.

Complex Trajectory with Complex Gravity Fields



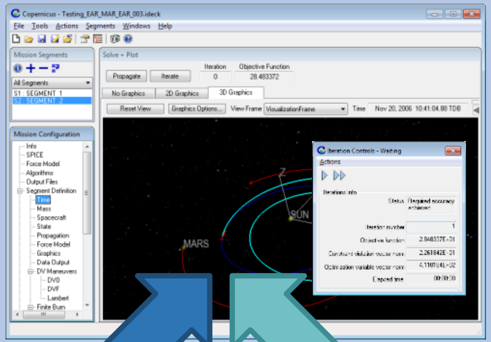
- Multiple spacecraft and propulsion systems.
- Segment to segment information inheritance.
- Plugins allow user-defined capabilities.
- Optimization variables and constraints.
- Forward and backward propagation.

The simple segment construction method can be used to create anything from a simple trajectory to an extremely complex set of interdependent trajectories .

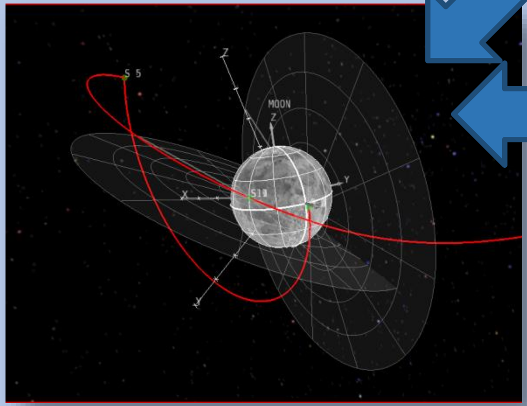
Ground Based Function

Copernicus marries a powerful computation engine with a friendly GUI and an interactive OpenGL graphics visualization capability.

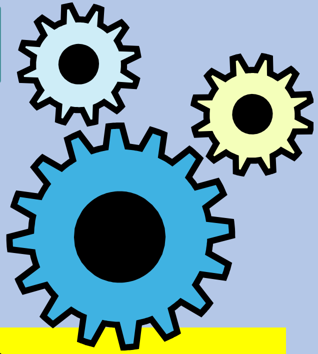
Main Program



GUI
User Inputs
Mission Design
Design Modifications
Numerical Feedback



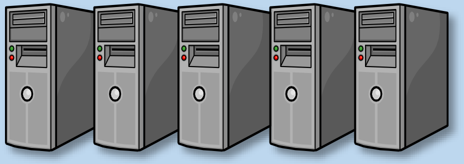
Visualization
Aid in Problem Set-Up
Trajectory Solution Feedback
“Real” Trajectory Insights



Engine
Trajectory Segments
Optimization
Integration
Control Algorithms
Engine Models

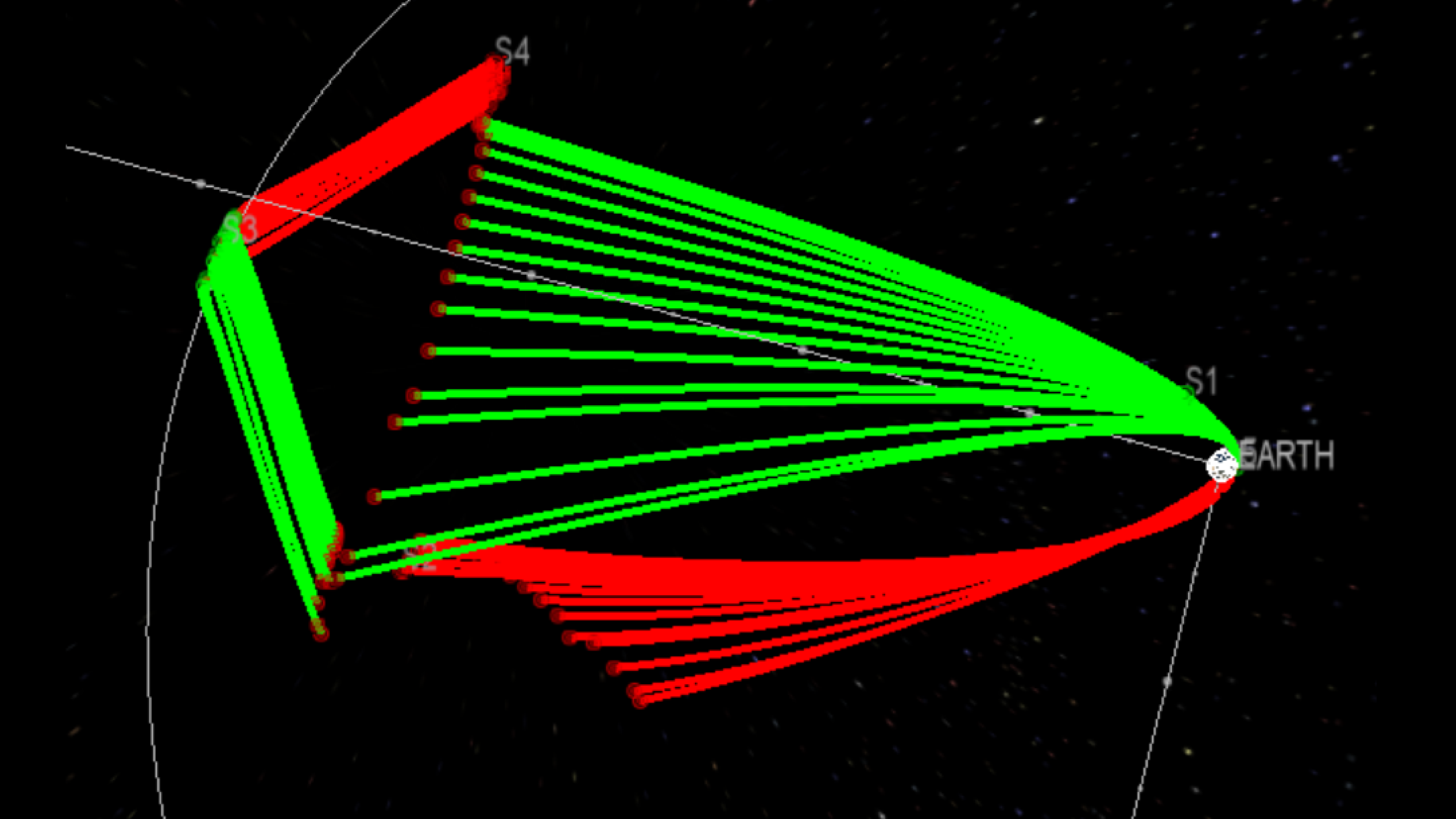
Copernicus Libraries

Toolkit Library
Celestial Mechanics Routines
SPICE Interface
Math Utilities
Coordinate Transformations
Binary File I/O
Gravity Models



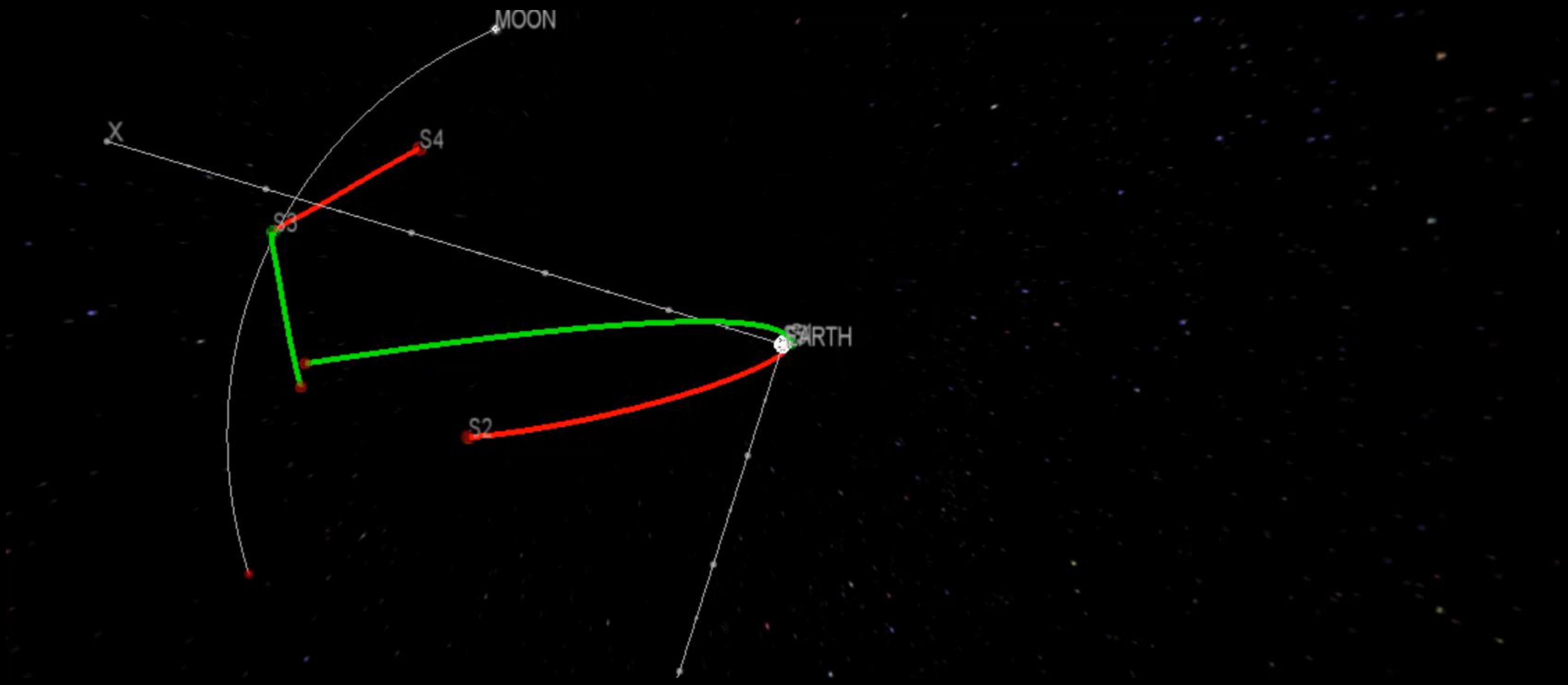
Batch Library
Distributed Processing
Automated Copernicus Runs
Production Data Output

The holy grail of trajectory optimization is finding the initial guess for the unknown set of optimization variables that converges to a solution, for any problem



S4
S3
S1
EARTH

Example 3: Construction of a Lunar Free Return



lfr-example-01.mp4

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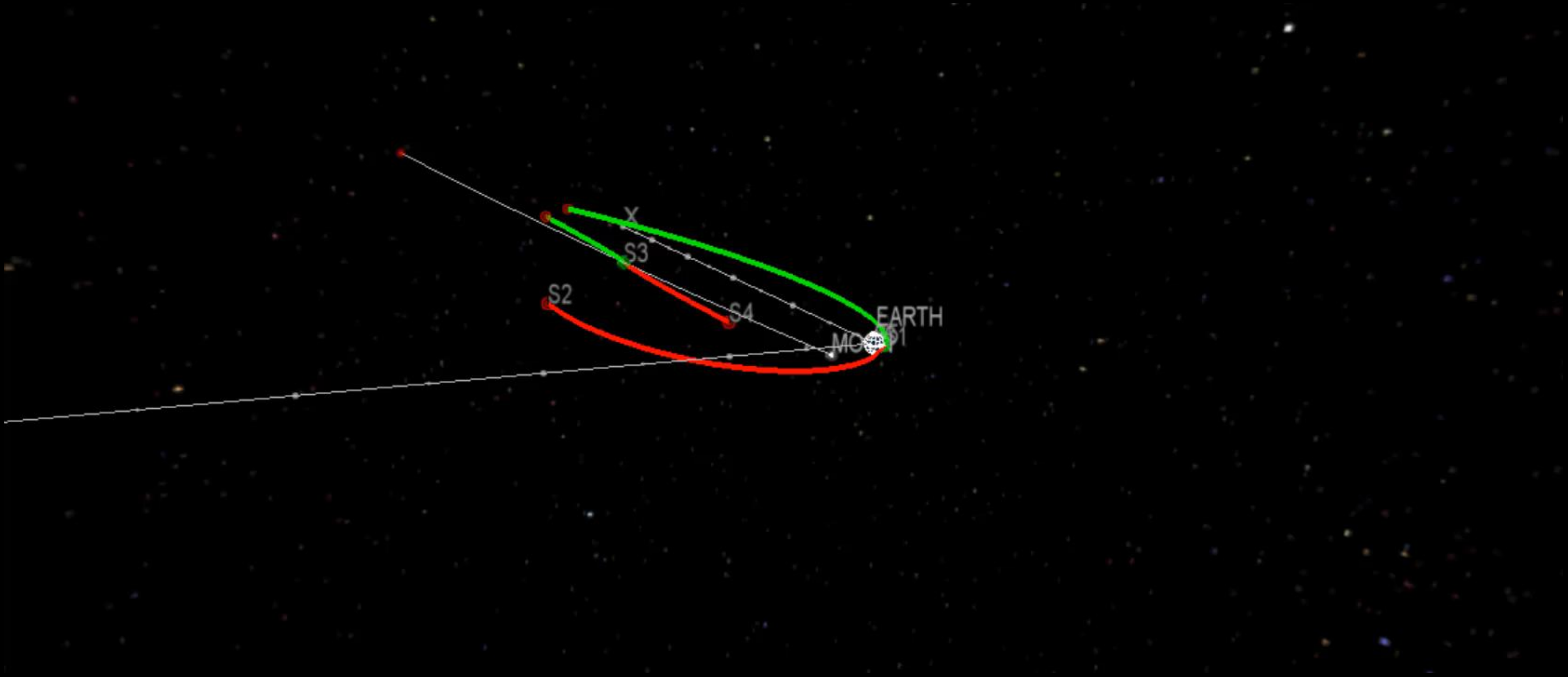

lfr-example-01.mp4

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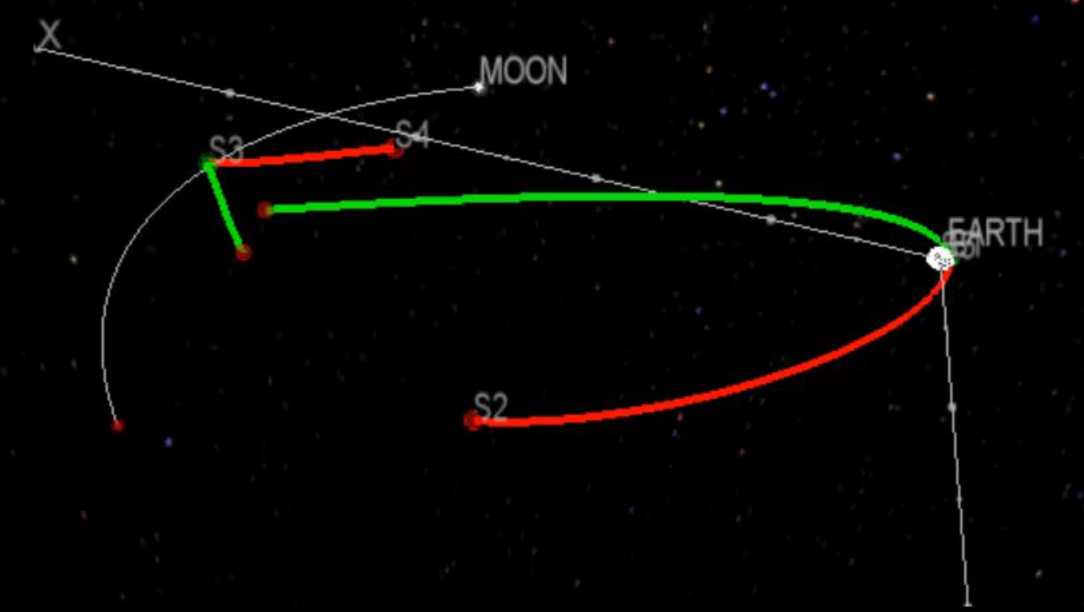

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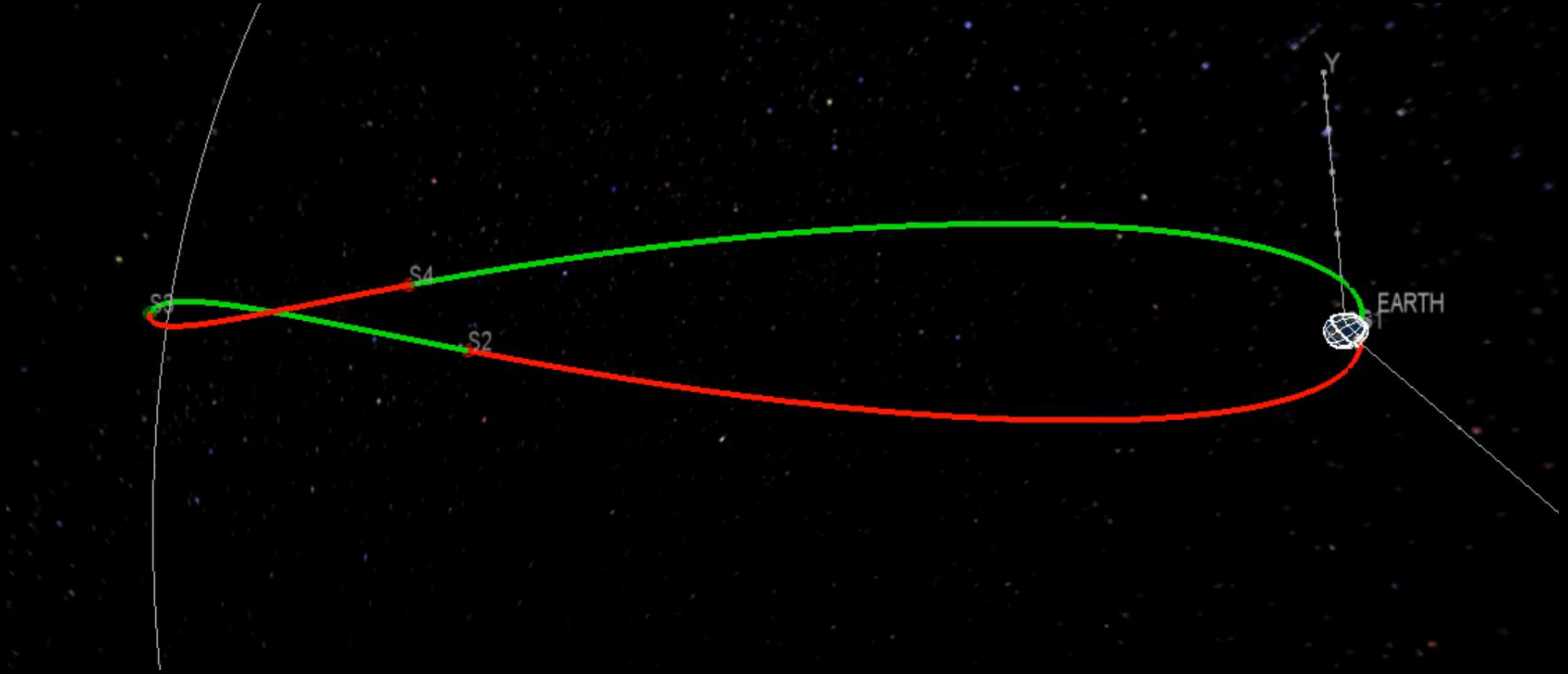
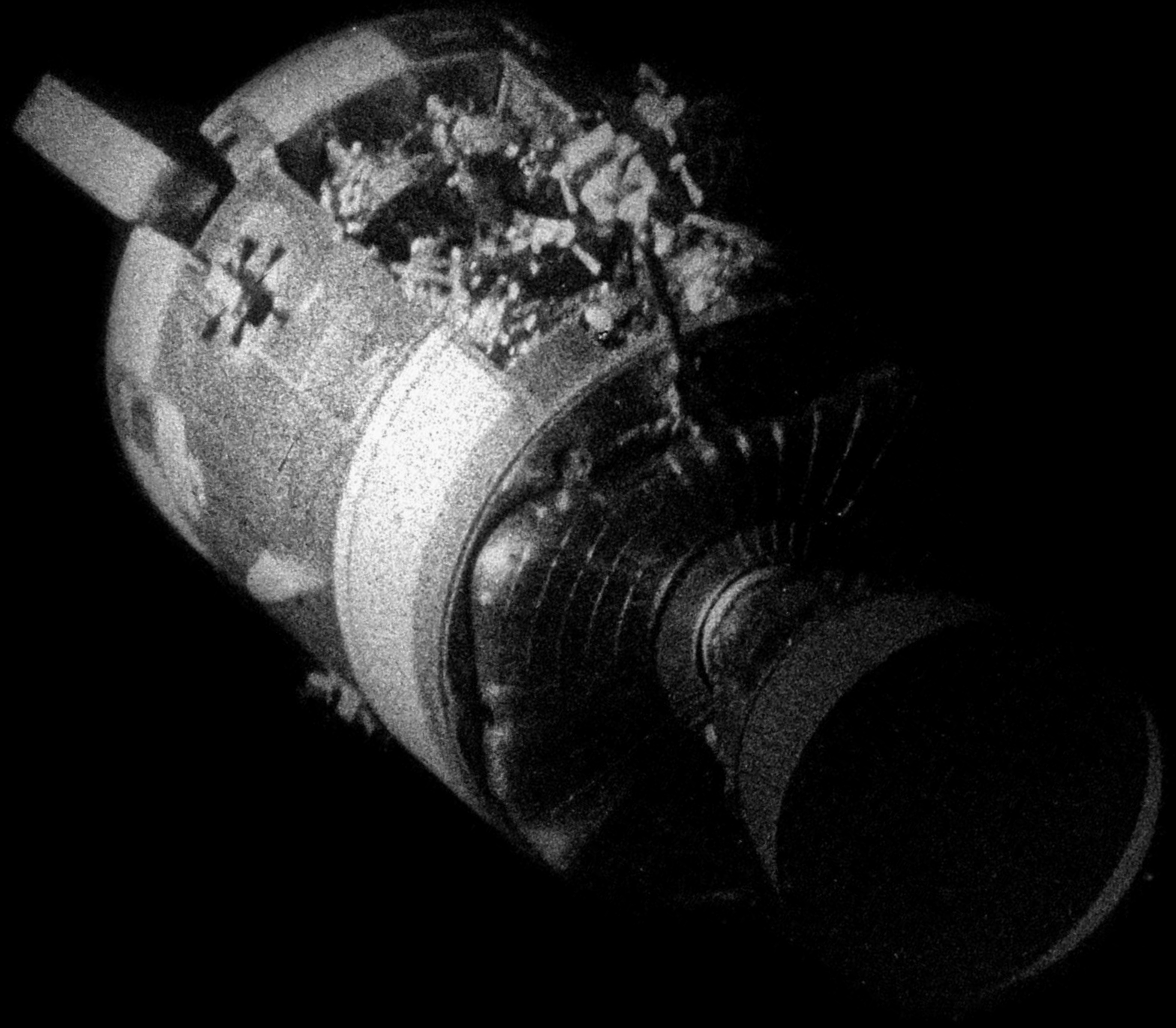
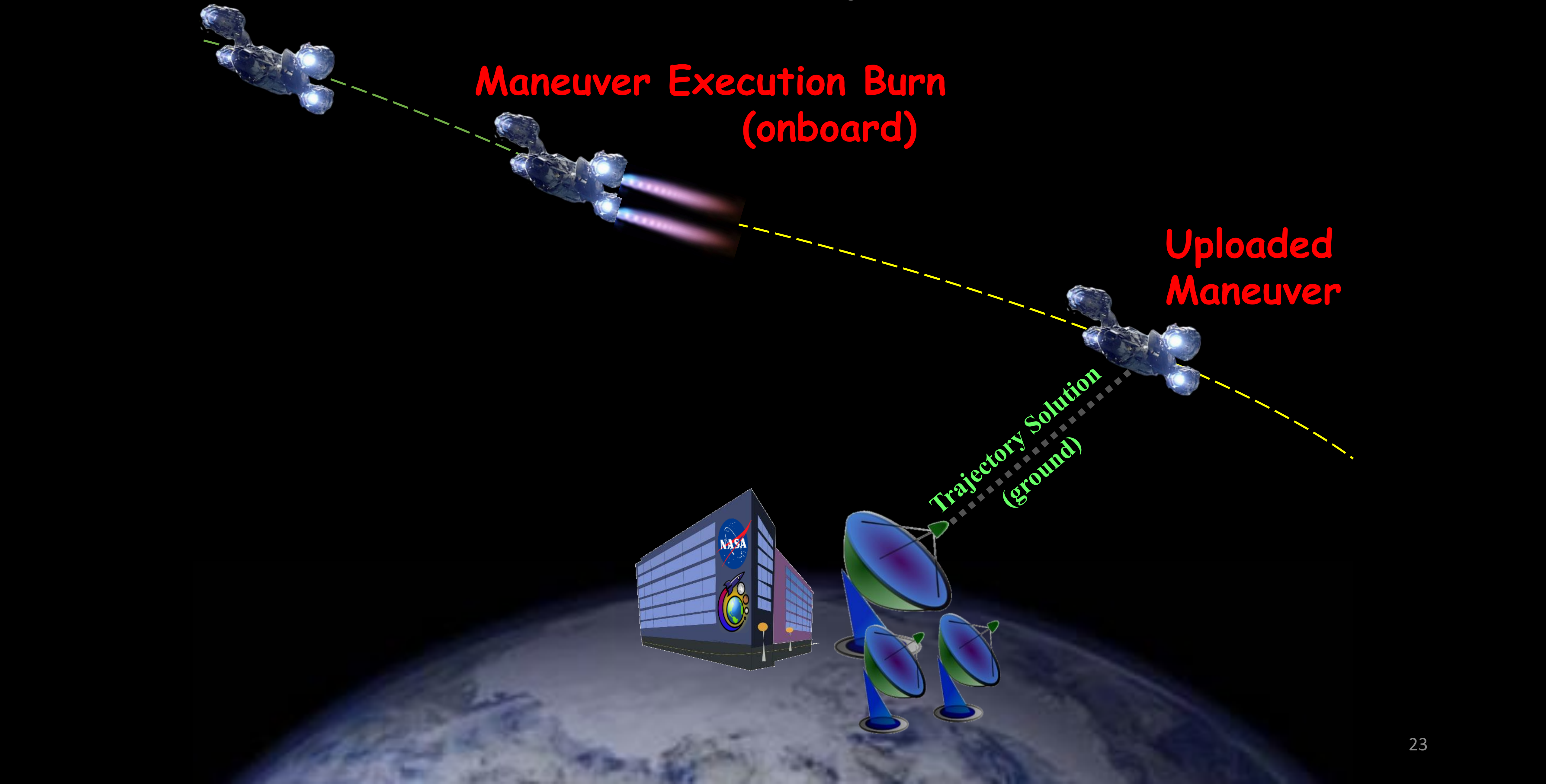


lfr-example-01.mp4

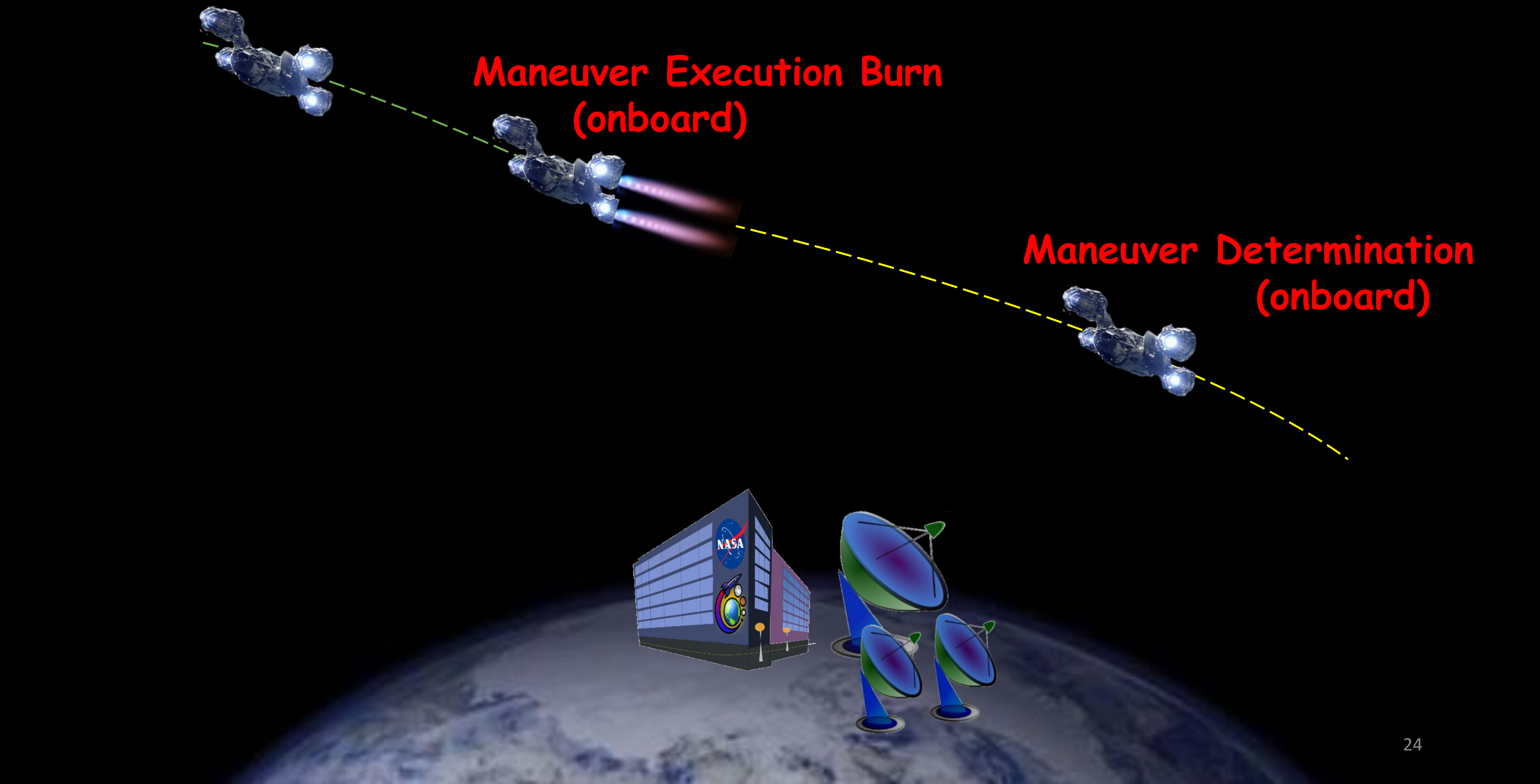
- Apollo 13 had a catastrophic failure
- Fortunately, and with the grounds intense intervention, the crew was able to return back to earth, safely
- If, on Apollo 13, the communications link had been also lost, most likely, the crew would not have returned home, safely
- The Apollo 13 incident most likely would not have been survivable but for the ground’s assistance.



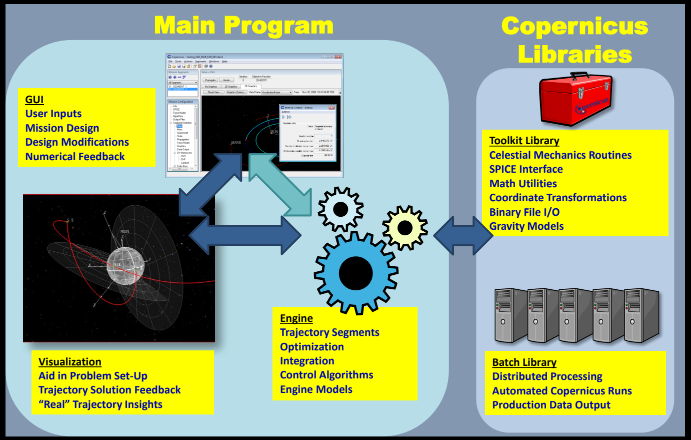
Ground Based Mission Planning / Maneuver Execution



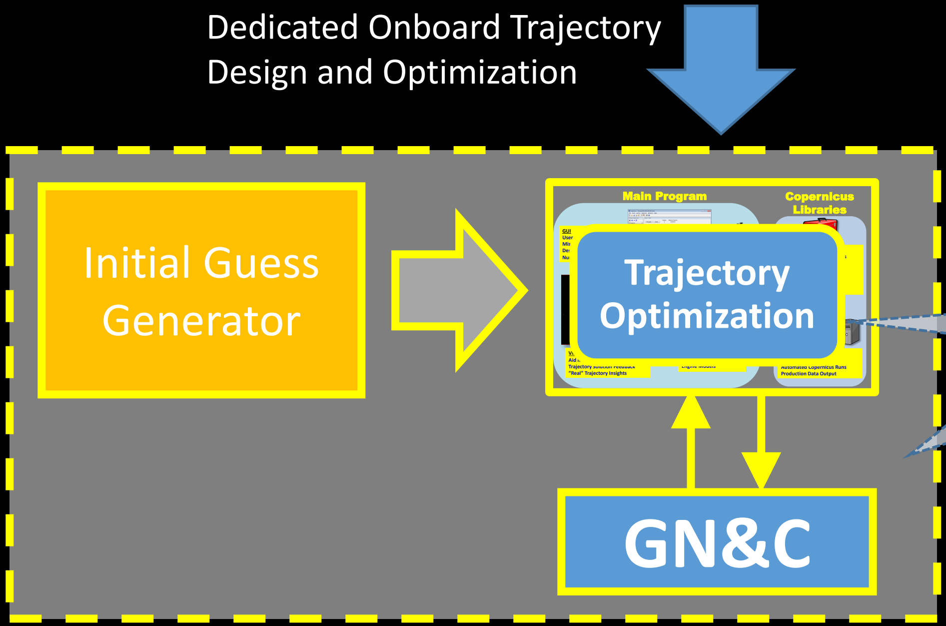
On-Board Based Mission Planning / Maneuver Execution

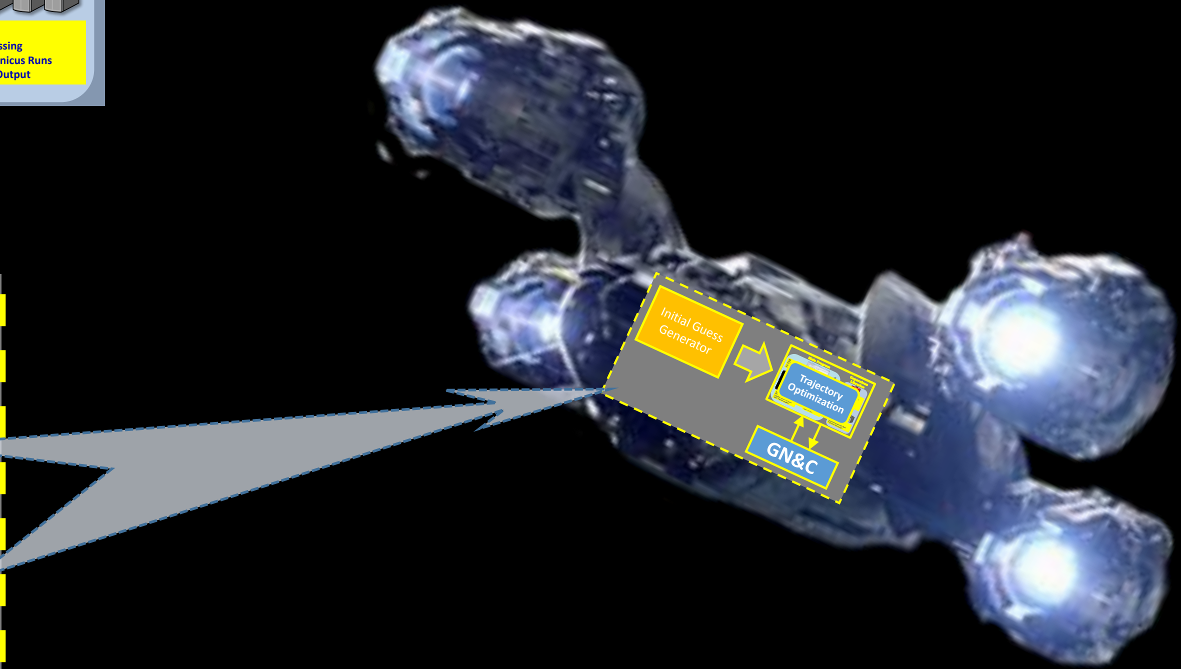


Moving Mission Planning (Algorithm Optimization) Onboard



Dedicated Onboard Trajectory Design and Optimization





Notional Onboard Scheme

Onboard

Onboard Flight Software

Maneuver Cmd. Data

Nav State Data
Epoch, Environment Data

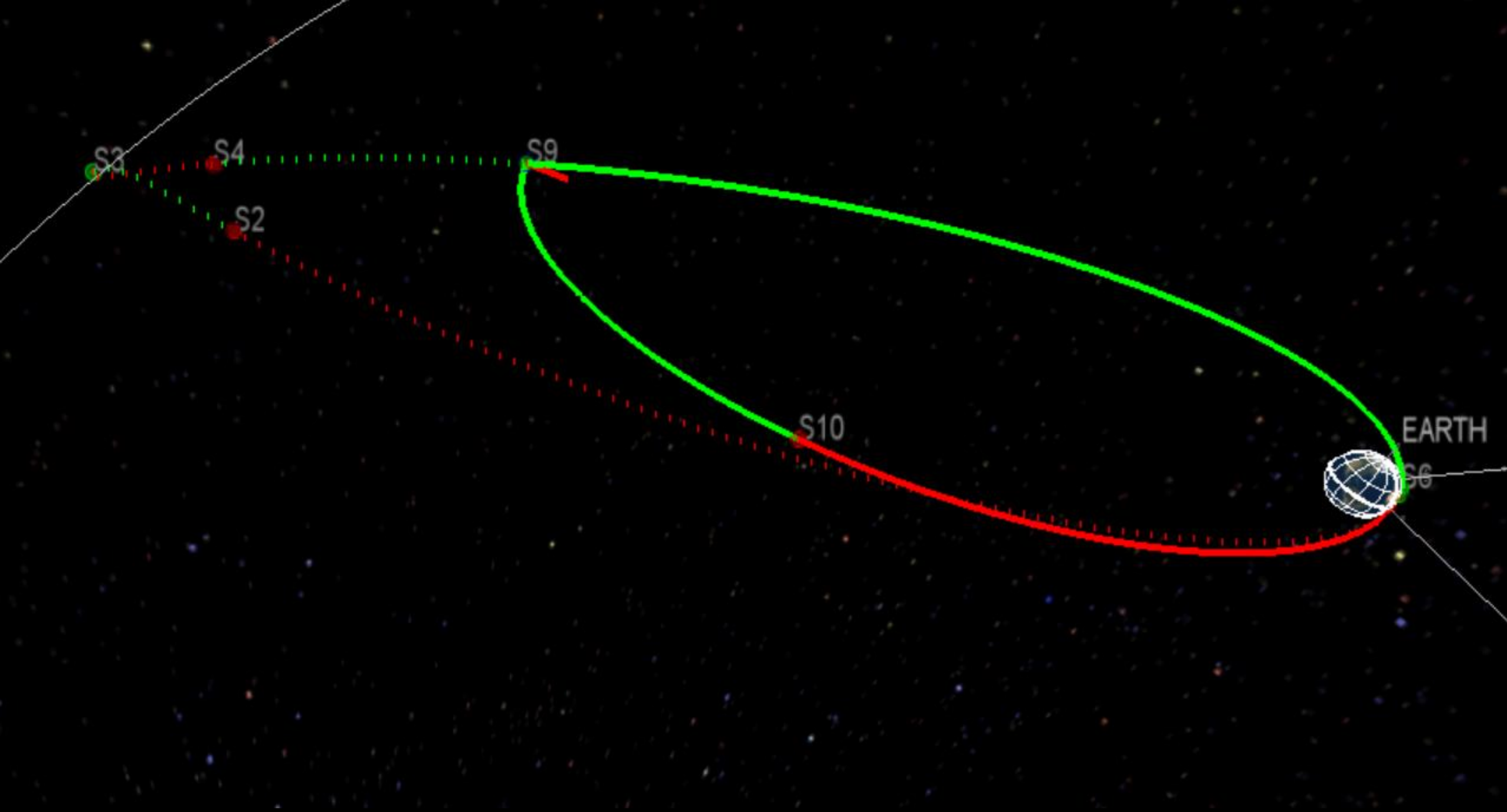
Current time
Current state
Current prop
Current mass
Engine Data
Mass
SRP Coef.
…

Copernicus
Interface Module
(Python Executive)

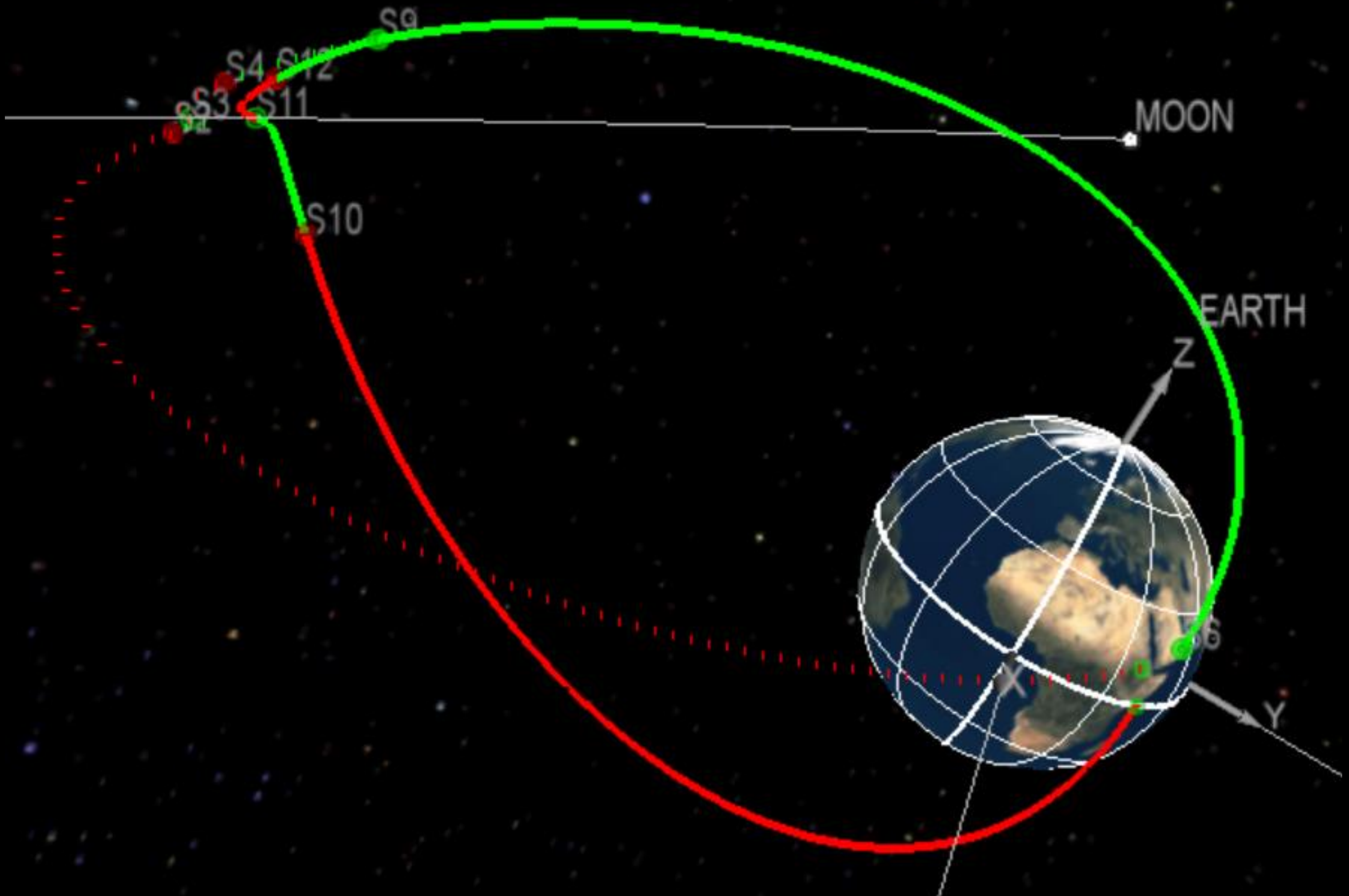
Current State
Propagated State
Maneuver times
Maneuver DVs
Maneuver duration
Other Future event details
…

File I/O
- Input decks
- Data files
- System calls

Initial Guess Generator (IGG)



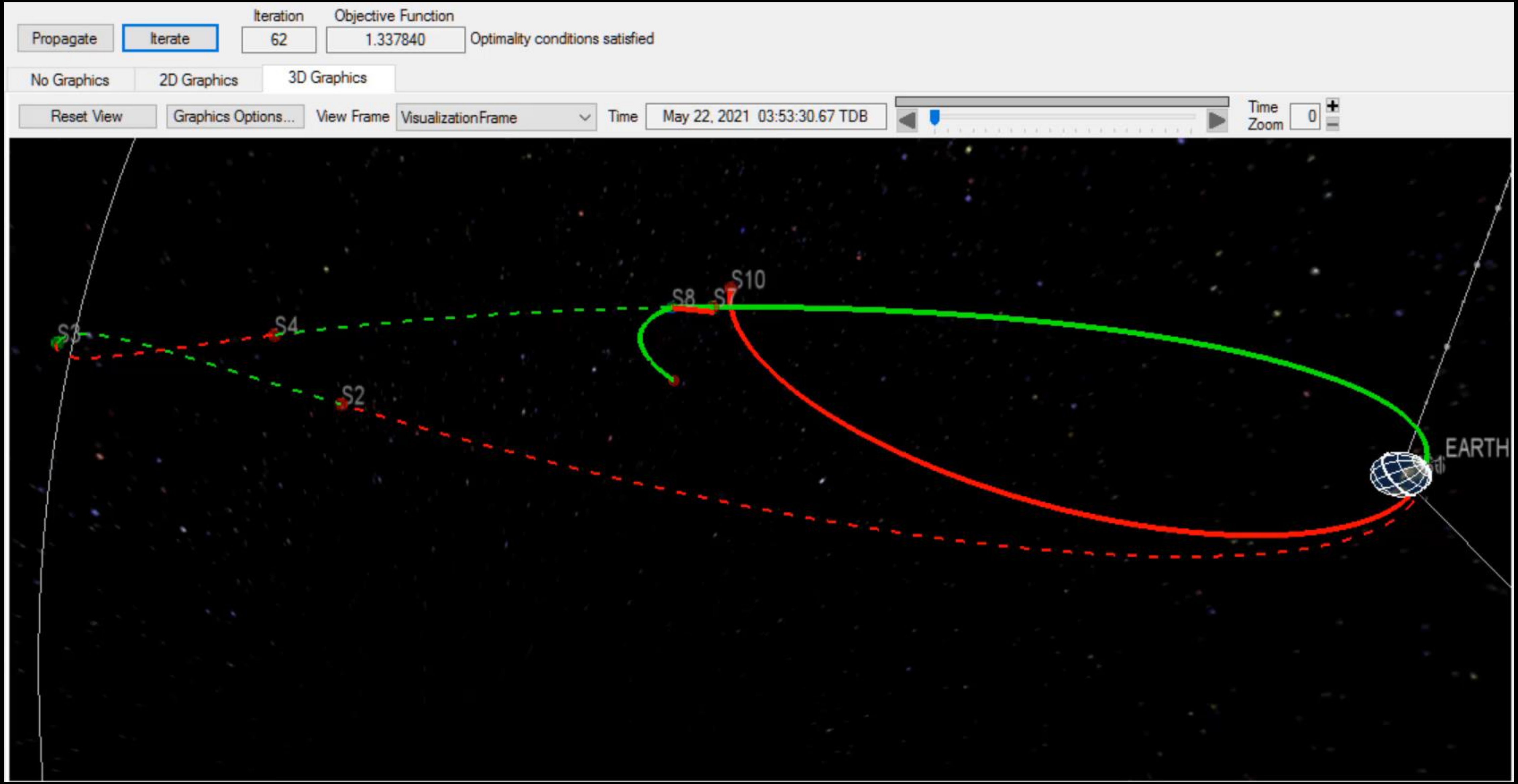
S3
S4
S9
S2
S10
EARTH
S6



S9
S4
S12
S3
S11
MOON
S10
EARTH
Z
X
Y

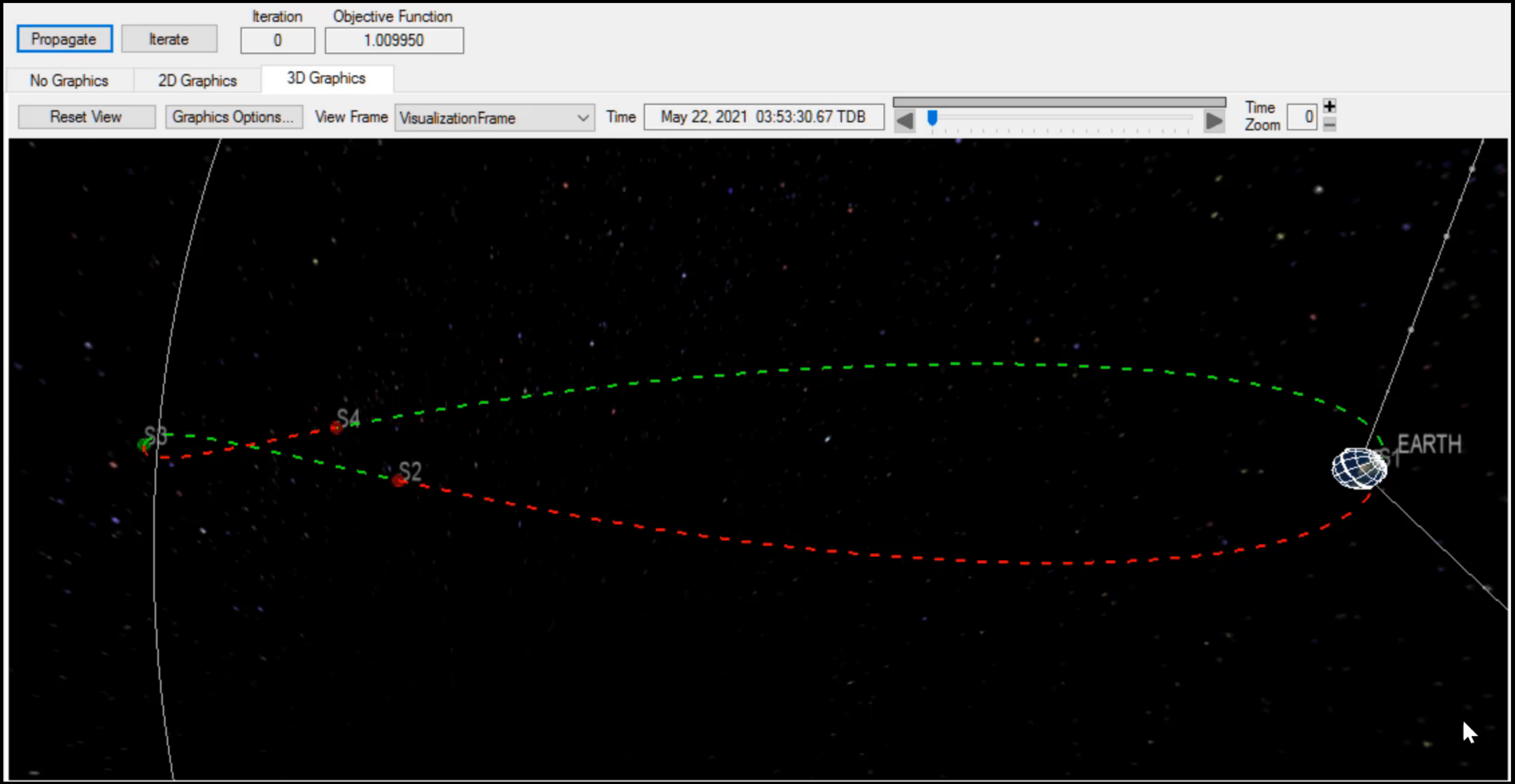
labort-ex01-01.mp4

Example 4: Abort to Direct Return



labort-ex01-02.mp4

Example 4: Abort to Direct Return



labort-ex01-03.mp4

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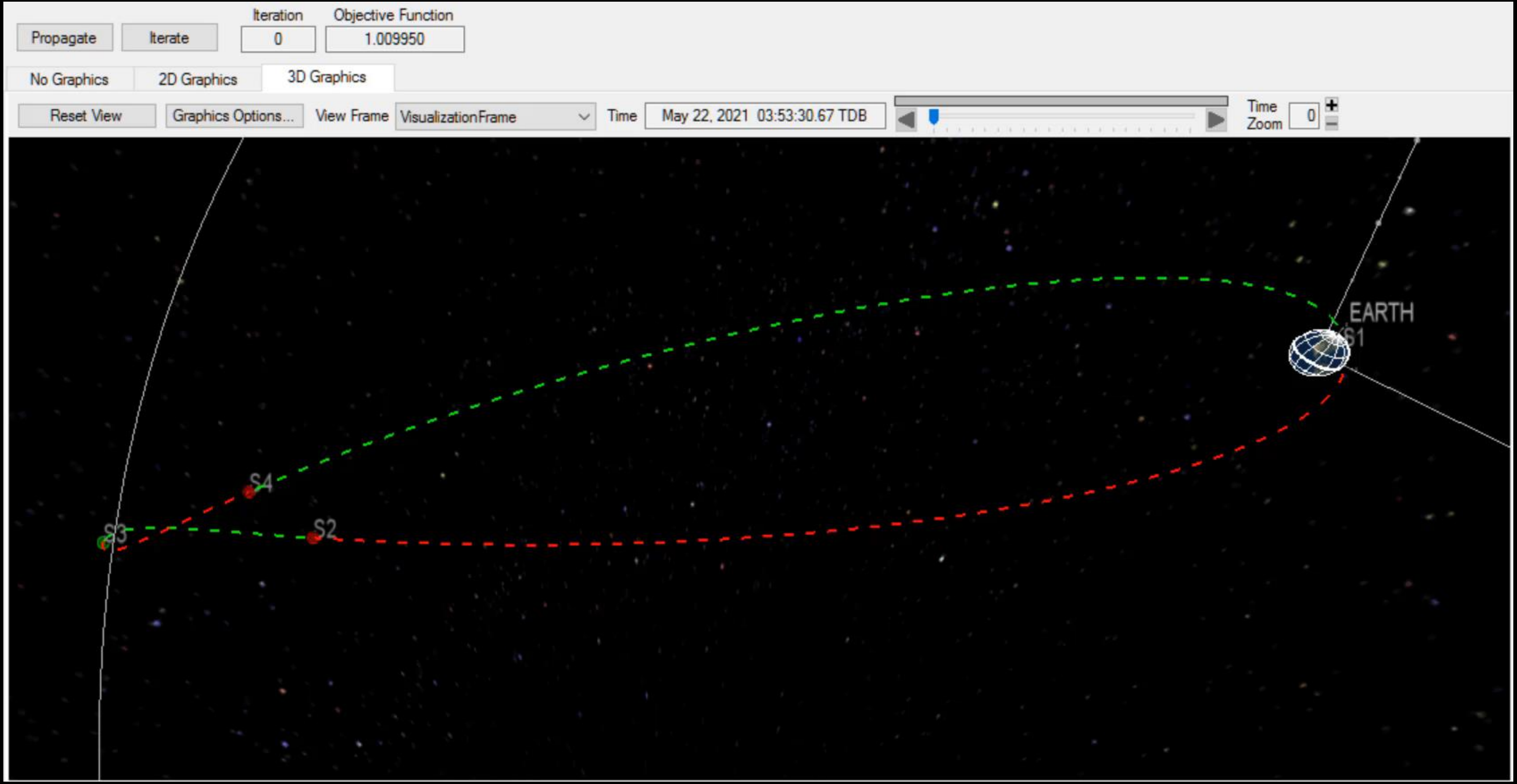

labort-ex01-04.mp4

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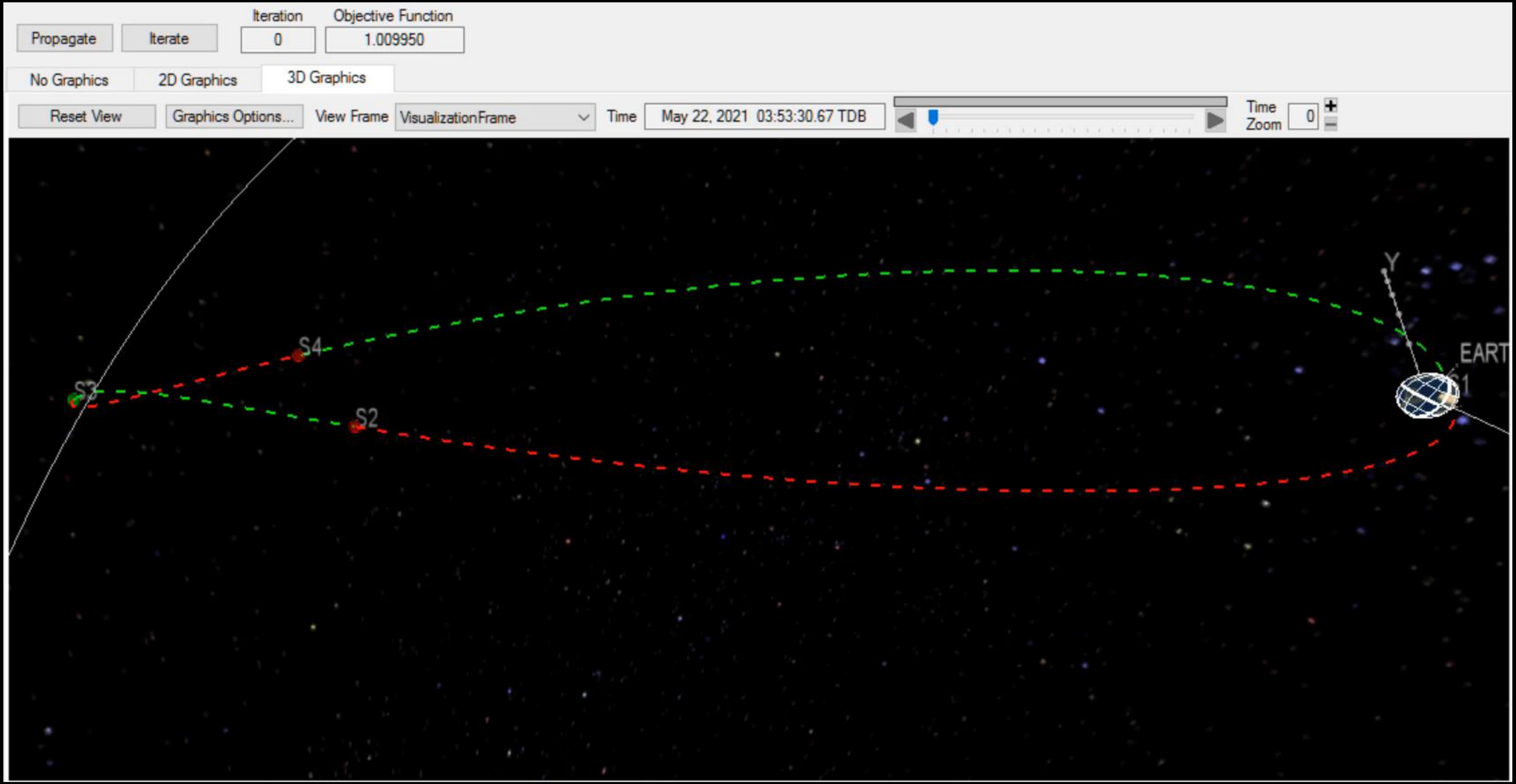
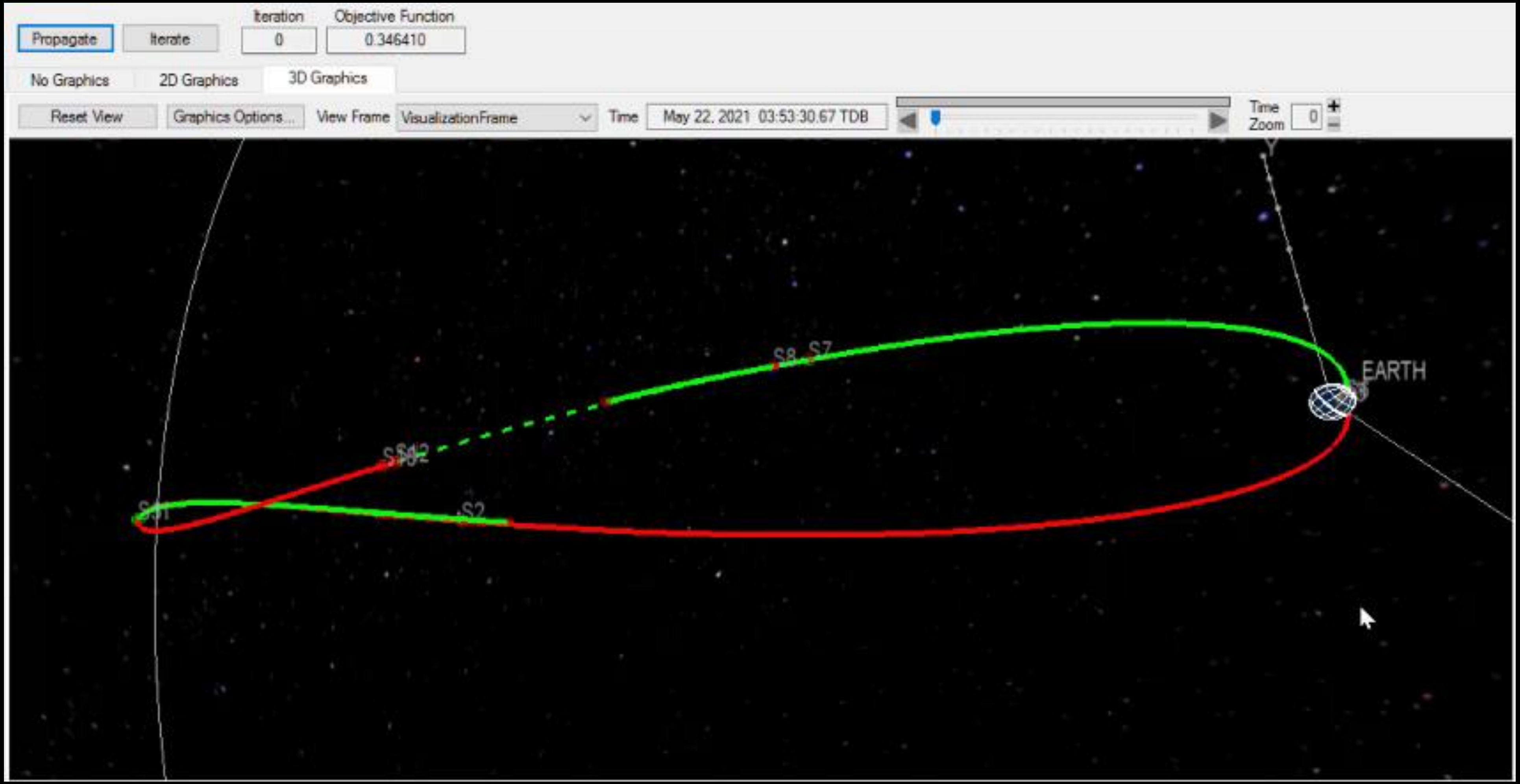


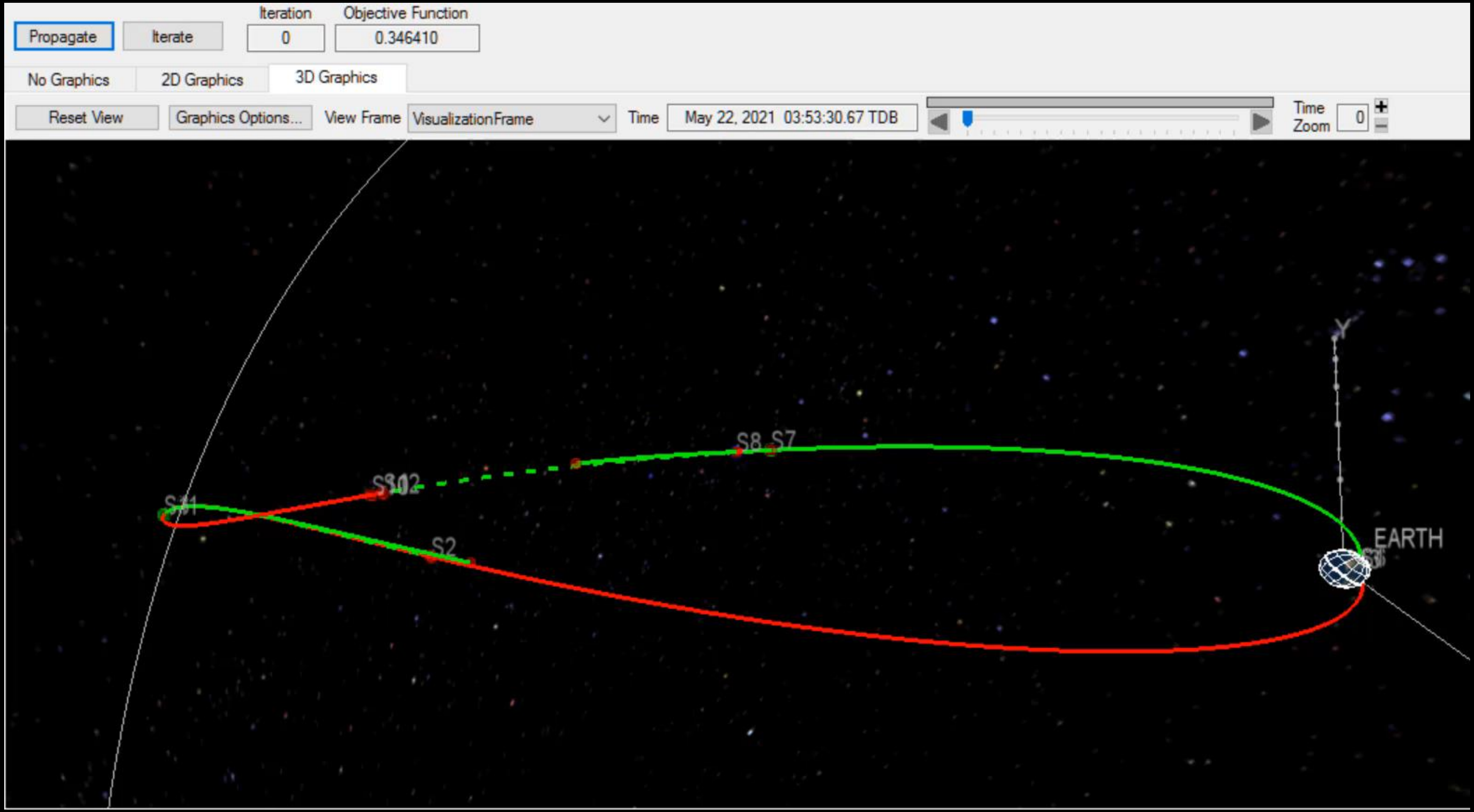
labort-ex02-01.mp4

Example 5: Abort to Moon Shorten Return Time



labort-ex02-02.mp4

Example 5: Abort to Moon Shorten Return Time



labort-ex02-03.mp4

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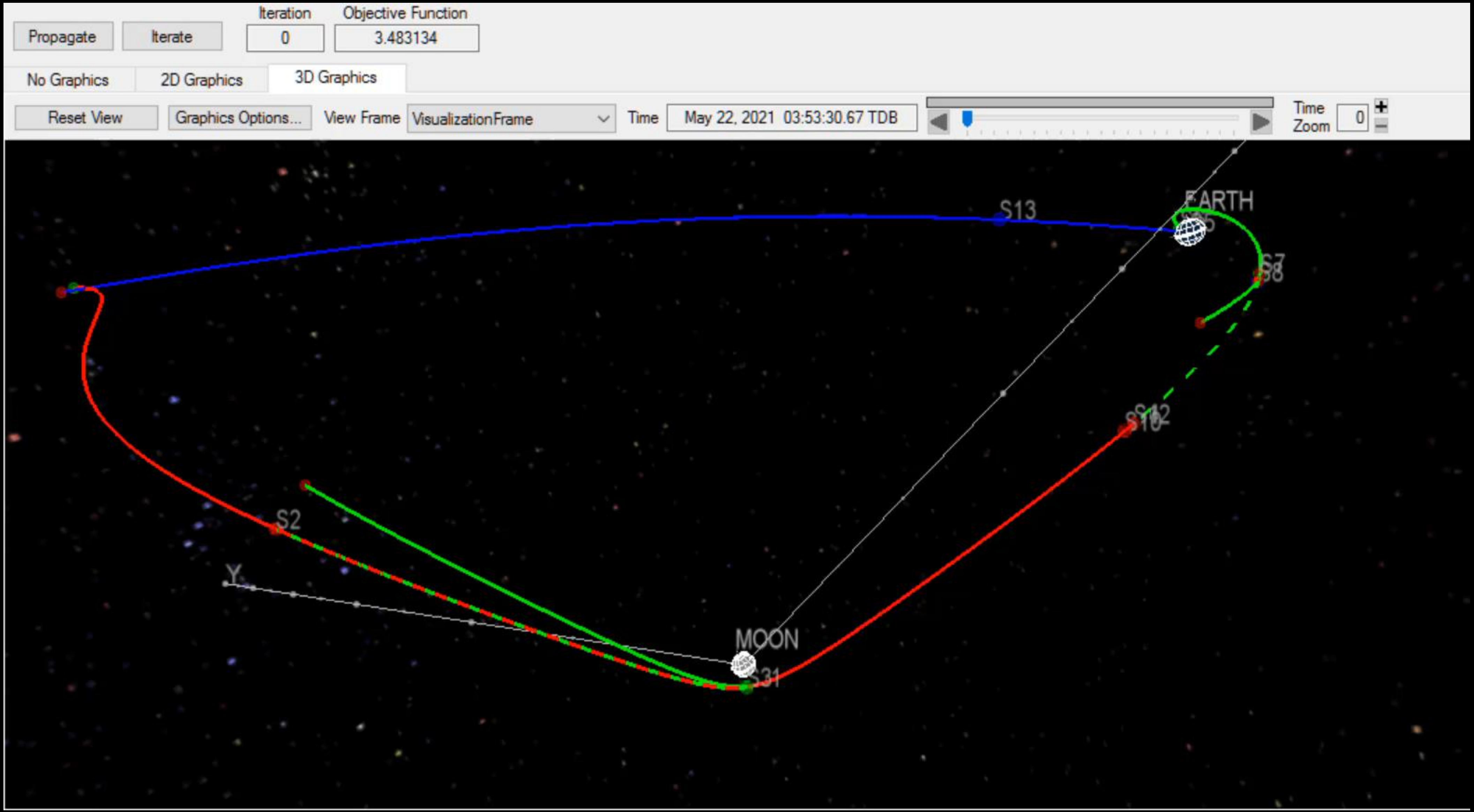
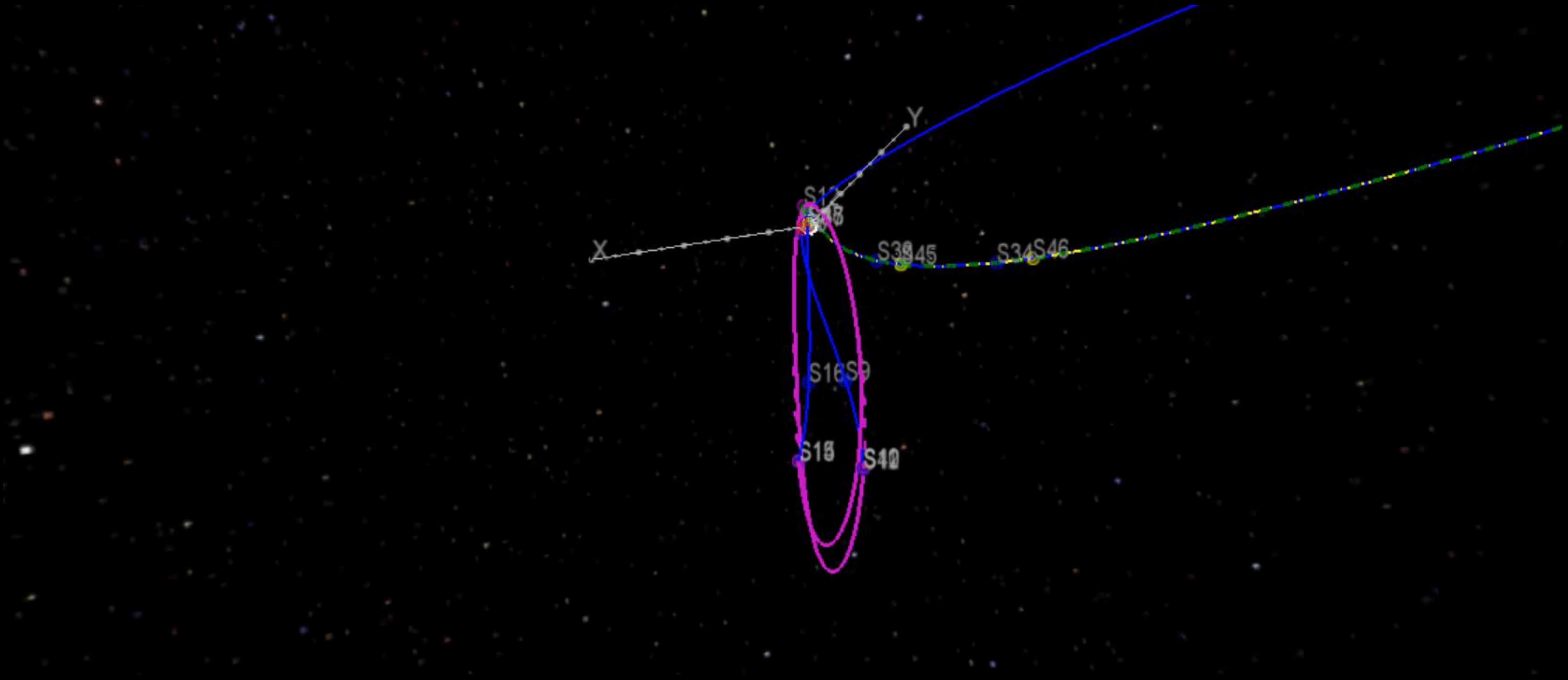


Other things that can be shown

- The EM-1 Trajectory
- The EM-2 Trajectory (the real one from Ricky)
- The EM-3 Trajectory (the nice NRO transfer)
- The ARM Trajectory

Figures of each of these will suffice

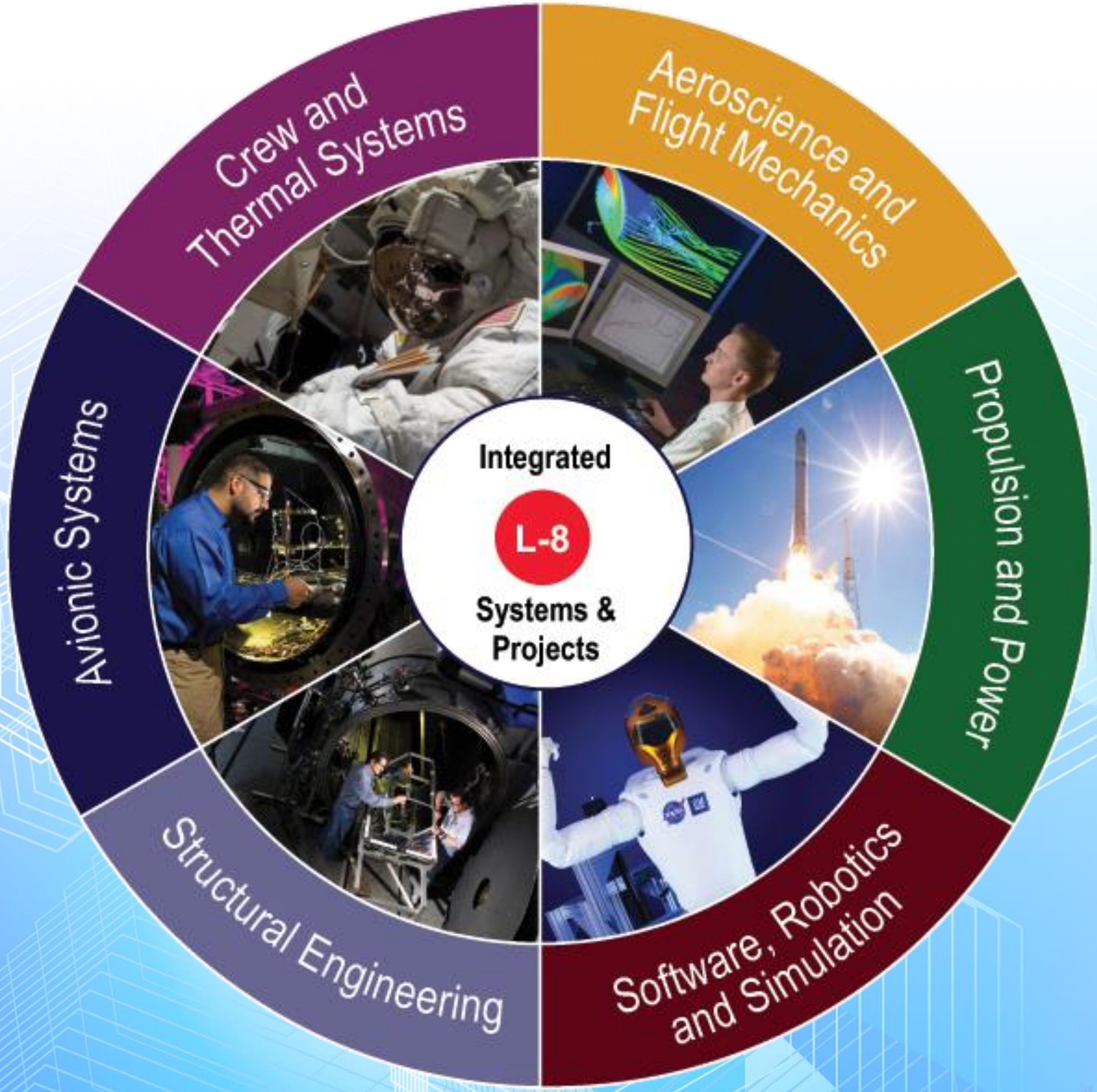
nro-mission-example.mp4



The key problems to solve for the future

- Pre-Flight
  - Open loop trajectory design and optimization---the 'initial guess' problem
    - Tools like the one you just saw (Copernicus) allows users to construct the initial guess by hand
    - It is possible, and we have done it, to construct Initial Guess Generators for any type of problem
- In-flight
  - Automatic replaning, or computing multiple abort options on the fly
    - Some will pose the problem of getting home the fastest with the given amount of prop remaining
    - Others will pose the problem of setting the return time, and minimizing the prop required to do so, so as to save fuel in case other problems come up

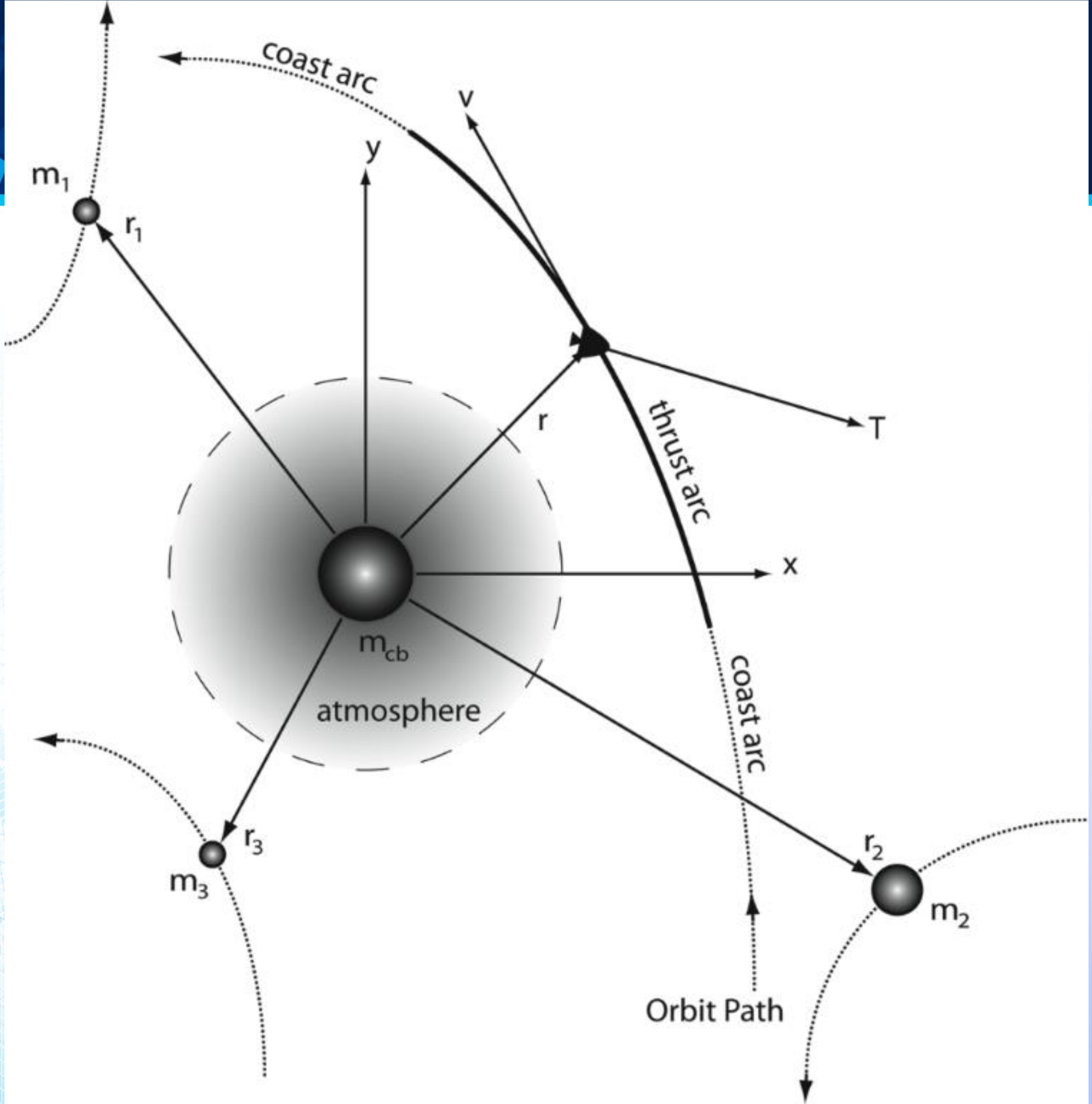
JSC Engineering: HSF Exploration Systems Development



- We want to ensure that HSF technologies are ready to take Humans to Mars in the 2030s.
- Our Goal: Get within 8 years of launching humans to Mars (L-8) by 2025
- We need collaborators to make it happen, and we think they can benefit by working with us.
  - Pointer to Co-Dev Announcements
  - Pointer to intake site

Boilerplate

Backup



coast arc
v
y
m_1
r_1
r
T
thrust arc
x
m_{cb}
atmosphere
coast arc
r_3
m_3
r_2
m_2
Orbit Path

Presentation Script

- Discuss the complex dynamics associated with spaceflight in complex force fields
  - Show Three examples of particle motion in the Earth-Moon, Sun-perturbed system
- Discuss the basic problem of trajectory optimization
  - Modeling the dynamics (as shown in the previous bullet of complex motion)
  - Simultaneous Targeting and Optimization of any quantity (typically min DV, or min time)
  - This main bullet should show a diagram that already exists….the cartoon diagram of several disconnected segments and how we need to connect them and optimize at the same time
- Discuss the importance of the initial guess and the importance of having a state of the art tool like Copernicus
  - Use the construction of the lunar free return as an example of this (show ideck movie of this)
  - Show several Copernicus idecks/videos that illustrate the iteration process graphically
  - Show an earth-mars-earth free return (how it is constructed, the final animated flight).
- Crew autonomy…not dependent on the ground segment…to deal with any event, especially those unforeseen, enroute.
  - An enroute abort calculations as examples.

On-board Mission Planning / Maneuver Execution

Ground Based Mission Planning / Maneuver Execution